2001

a fossil odyssey

SCIENCE AND RESEARCH ON PUBLIC LANDS

THE FOSSIL FERNS OF PETRIFIED FOREST NATIONAL PARK, ARIZONA, AND THEIR PALEOCLIMATOLOGICAL IMPLICATIONS

SIDNEY ASH
Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131

ABSTRACT—Approximately one-fifth (ten species) of the plant megafossils in the Chinle Formation in Petrified Forest National Park, Arizona are the remains of ferns or fern-like leaves. Four of the species are assigned to living families, two are assigned to extinct families and the others are unassigned. The nearest living relatives and morphological features of these plants indicates that they lived under a humid tropical to subtropical climate that could have been monsoonal.

INTRODUCTION

Although, it was originally established to protect the large numbers of petrified logs that occur there, Petrified Forest National Park in east-central Arizona (Fig. 1) also contains significant deposits of compressed leaves, seeds, cones, and other plant parts, all of which occur in the Chinle Formation of Late Triassic age (Late Carnian and Early Norian Stages). Some of the most abundant of these compression fossils are the remains of ferns and fern-like foliage. At present this significant part of the flora consists of ten well-characterized species based on megafossils (Table 1). It will be useful now, at the beginning of the new millennium, to summarize what is now known about them and their paleoclimotological implications. The numerous dispersed fern spores found in the park that were described by Litwin (1984, 1986) and Litwin, et al. (1992) are beyond the scope of this article and are not considered here although they support the conclusions reached in this article.

GEOLOGIC BACKGROUND

The Chinle Formation was deposited in a large continental basin that was situated a short distance north of the equator on the west coast of Pangea (Blakey, 1989). It is composed of strata deposited by northward-flowing streams and rivers and in lakes and on flood plains in a succession of incised paleovalley cut-and-fill complexes (Dubiel, et al., 1999). The unit is now exposed over broad parts of the Colorado Plateau and because of its environment of deposition is subdivided into several understandably discontinuous units (Stewart. et al., 1972). In Petrified Forest National Park the formation is about 300 m thick and is conventionally (see Dubiel, et al., 1999) divided into the Shinarump, Mesa Redondo, Monitor Butte, Petrified Forest and Owl Rock Members (Fig. 2). The Sonsela Sandstone Bed, a persistent and distinctive lithologic unit, occurs between the Monitor Butte and Petrified Forest Members and is of some correlative value in the eastern part of the Colorado Plateau. Another noteworthy unit, the Newspaper Sandstone Bed, is present locally in the Monitor Butte Member in the park.

In Petrified Forest National Park, petrified wood occurs in large quantites in the Sonsela Sandstone Bed and subadjacent strata of the Monitor Butte Member. It also occurs there in smaller quantites at several other horizons in both the Monitor Butte and Petrified Forest Members (Ash and Creber, 1992). The largest concentrations of petrified wood in the park are termed forests and given names that reflect some particular aspect of the wood (Ash, 1987). In the southern part of the park they are Rainbow Forest, Crystal Forest, and Jasper Forest (Fig. 1). The wood in them was

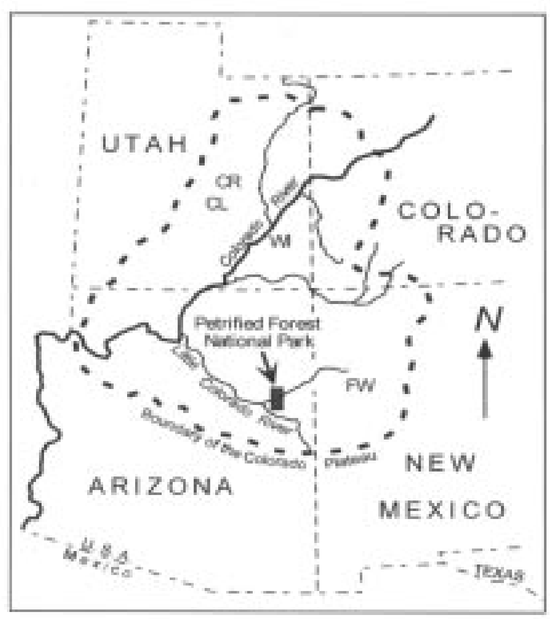


FIGURE 1. Map of part of the western United States showing the boundary of the Colorado Plateau and the location of Petrified Forest National Park and the other localities where significant numbers of Late Triassic ferns have been found. CL=Circle Cliffs, CR=Capitol Reef, FW=Fort Wingate, WI=White Canyon.

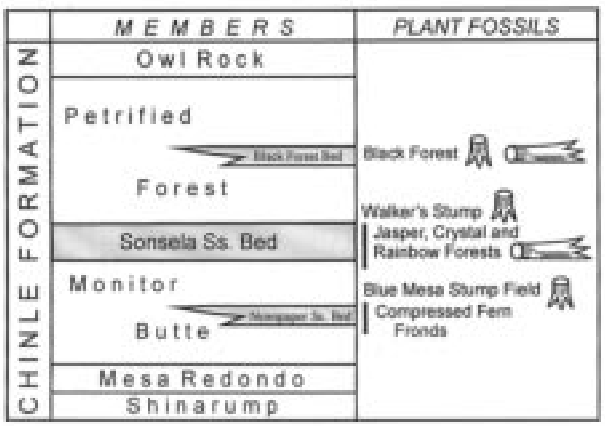


FIGURE 2. Diagram showing the members and other units of the Chinle Formation in Petrified Forest National Park and the relative positions of the petrified forests, the stumps that are in the position of growth, and the major deposit of compressed ferns. Adapted from several sources, particularly Dubiel, et al., 1999 and Ash, 1987.

derived from the Sonsela Sandstone Bed and the uppermost part of the Monitor Butte Member. Another forest occurs in the Black Forest Bed in the Petrified Forest Member and because the wood is black is called the Black Forest. Most of the wood in the forests consists of long prostrate logs and short broken sections but in the Black Forest Bed and the Monitor Butte Member there are a few stumps that are in growth position. In contrast, the deposits of compressed plant remains are much less common and are smaller in extent than the forests. The largest of the compressed plant deposits are found in the Monitor Butte Member adjacent to the Newspaper Sandstone Bed. Smaller deposits occur elsewhere in the Monitor Butte Member and in the Petrified Forest Member. In many, if not all cases, the compressed plant deposits occur either in overbank deposits or in local swamp deposits. None of the deposits in the Petrified Forest cover more than a few hundred square meters and the ferns only occur in the one that is associated with the Newspaper Sandstone Bed (Fig. 2). At other localities beyond Petrified Forest National Park, compressed plant fossils also occur only in the lower part of the Chinle Formation in the Shinarump and Monitor Butte Members mainly (Ash, 1989).

PREVIOUS INVESTIGATIONS

Fossilized remains of ferns were not discovered in the Petrified Forest or anyplace else in the American southwest until nearly a century after representatives of the conifers and cycadophytes were first found in the Chinle Formation (Ash, 1972b). Probably the principal reason that they remained undetected for so long is that fern fossils, like their living counterparts, are relatively delicate and are typically preserved in fine-grained rocks which had not been adequately investigated until the early part of the last century.

Fern fossils were first observed in the Chinle Formation during the early 1930s by the CCC crew that was building an all-weather road through Petrified Forest National Park (Ash, 1972b). The fossils occurred in grayish mudstones adjacent to the Newspaper Sandstone Bed in the Monitor Butte Member in a cut that the crew was excavating for the roadbed in the central part of the park near the Tepees (Fig. 3). The workers found compressions of fern fronds, some of which were complete and compressed leaves, cones and seeds of horsetails, cycadophytes, conifers, and other plants. Fortunately for science, Myrl Walker, the first naturalist appointed by the park, recognized the importance of the discovery and saw to it that many of the fossils were collected and preserved for exhibit and research. Later he arranged for their study by Lyman Daugherty, a botanist at San Jose State University in California. The results of his investigation were published a few years later (Daugherty, 1941). In the report, Daugherty described a total of 38 species based on megafossils, including eleven species of ferns and fern-like foliage assigned to nine genera (Table 1). Seven of them were new and three were known previously from the Late Triassic Newark Group in the eastern United States. Daugherty later (1960) described the trunk of a new tree fern from the Petrified Forest. Shortly afterwards, I began a reinvestigation of the Chinle flora, basing my work on new material collected from localities throughout the Southwest as well as from Petrified Forest. During those investigations I re-evaluated all of Daugherty's species of ferns and fern-like foliage (Ash, 1970, 1972a, 1973, 1994, 1999). Although most of his identifications were accepted, I redescribed several of his species using new techniques, and in some cases reassigned them to different and sometimes new genera. More recently, a new dimension was added to the biology of these plants when the evidence that some of them had been used by arthropods for food and shelter was discussed (Ash, 1997, 1999, 2000).

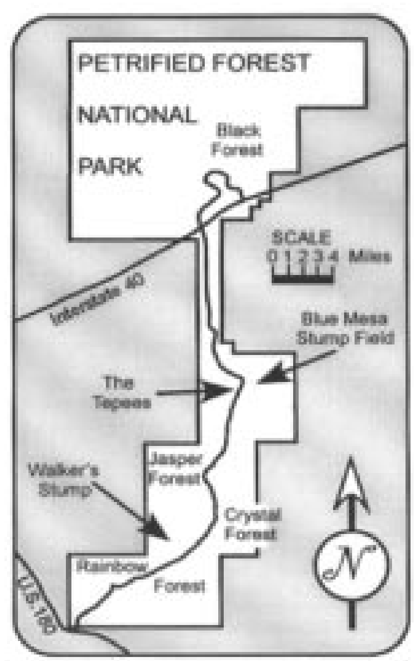


FIGURE 3. Map of Petrified Forest National Park showing the location of the forests and other features discussed in this article. Adapted from Ash, 1987.

SYSTEMATIC REVIEW

Here, the salient features of each of the megafossils assigned to the ferns and the fern-like foliage found in the Chinle Formation in Petrified Forest National Park, Arizona are briefly described. The ferns are considered systematically under their assigned family and then the species based on fern-like foliage are discussed. Detailed descriptions and more illustrations of the fossils appear in the articles cited. Illustrations of each species based on leaves are given in Fig. 4. The key to the species given in Table 1 will assist with the identification of the leaves of fossil ferns or fern-like foliage discovered in the park by future investigators.

Family Osmundaceae

The only representative of this living family found in the park is *Todites fragilis* Daugherty emend. Ash, 1970. The leaf is small (largest specimen is 6 cm wide, 12.5 cm long), delicate, and bipinnate and has distinctly asymmetrical pinnae (Fig. 4E). On the lower side of the rachii of the pinnae the lamina is narrow and undivided, whereas on the upper side the lamina is broad and near the main rachis of the leaf is divided into several ovate pinnules, but it becomes progressively less divided apically and eventually becomes totally undivided. Venation consists of a midvein which gives off lateral veins alternately. Fertile and sterile pinnae occur on the same leaf. The sporangia are solitary on the lower surface of the pinnules and are round to oval with a subapical annulus. Small, round to slightly triangular trilete spores similar to the dispersed spore *Osmundacidites parvus* De Jersey (see Litwin, 1984) are produced in the sporangia on the distinctive leaves assigned to this species. *Todites fragilis* is relatively rare and is known only from the Monitor Butte Member of the Chinle Formation in Petrified Forest National Park and in the Fort Wingate area, New Mexico (Ash, 1970). Living members of this family typically inhabit humid subtropical to tropical parts of the world such as southeast Asia.

Family Guaireaceae

Itopsidema vancleaveii Daugherty (1960) is the petrified stem of a small treefern which is about 15 cm in diameter and when alive, probably was only about one meter tall. While the plant was living the stem would have been relatively soft and spongy and held upright by a mantle of numerous adventitious small roots. The sides of the stem were covered with the broken bases of many leaves and a crown of large leaves of unknown type was present on the top of the stem. Although, this fossil was originally assigned to the Osmundaceae by Daugherty (1960) recent investigations indicated that it should be assigned to the Guaireaceae, an extinct family of Mesozoic ferns (Ash, 1994). The only specimen of this species was collected from the Monitor Butte Member of the Chinle near the base of Agate Bridge Mesa (Daugherty, 1960; Ash, 2000).

Small coprolite-bearing cavities reported by Ash (2000) in this fossil indicate that the living plant provided shelter and food for mites. The cavities occur in and near the leaf petioles and in the root mantle, are round to irregularly shaped and range up to a few millimeters in diameter. Although the cavities are not lined with reaction tissue, a few masses of it are present in some of the cavities, indicating that the plant was alive when attacked. The coprolites are oval to weakly hexagonal in shape and the largest are slightly less than 0.1 mm in length. The mite responsible for the damage is unknown. Modern treeferns live in humid tropical and subtropical parts of the world.

Family Cynepteridaceae

Cynepteris lasiophora Ash (1970) is the only known representative of this extinct family of ferns. The fossil is a large (24 cm wide, possibly 1 m long) bipinnate leaf in which the pinnules are generally oblong and have reticulate venation (Fig. 4H). Fertile and sterile pinnules occur on the same pinna. The sporangia are solitary and are irregularly scattered on the lower surface of the pinnules or concentrated on just the basal parts. They are oval to pear-shaped and have a complete apical annulus. Spores of *Cynepteris lasiophora* are small and round to subtriangular and are comparable to the dispersed spore *Verrucosisporites* sp. C of Bharadwaj and Singh (see Litwin, 1984).

Some of the leaves of this distinctive fern show evidence of having been the source of food for phytophagous insects (Ash, 1997). This evidence consists of excisions along the margins of the pinnules where a portion of the lamina has been removed. In some places crescent shaped portions of the lamina were removed whereas in other places the excisions are more or less straight, paralleling the pinna rachis and cut across several pinnules. The margins of the excisions are sharply defined and unfrayed. Typically the excisions are bordered by a narrow zone of reaction tissue that includes both callus and necrotic tissue, indicating that the feeding occurred while the leaves were alive and still attached to the parent plant.

Cynepteris lasiophora is one of the most abundant and widespread of the ferns in the Upper Triassic of the western United States where it has been described from the Chinle Formation in Petrified Forest National Park, in the Fort Wingate area of New Mexico, and the White Canyon, Circle Cliffs, and Capitol Reef areas in southeastern Utah, as well as in the Dockum Group near Santa Rosa in eastern New Mexico and near Amarillo in west Texas (Ash, 1970; 1972c).

Family Gleicheniaceae (?)

Wingatea plumosa (Daugherty) Ash (1970) is tentatively assigned to this living family. The fossil is a large (up to 12 cm wide, 50 cm long), highly dissected tripinnate leaf with very small ultimate segments that vary in outline from oblanceolate to narrowly lobed (4F). Venation is dichotomous with a single vein in each lobe. Fertile and sterile pinnae occur on the same leaf. The sporangia are clustered in ring-like sori on the backs of the fertile pinnae and include 8-12 sporangia. The annulii on the sporangia are obliquely horizontal apical rings. The spores produced in the sporangia are rounded triangular and reportedly (Litwin, 1984) are similar to the dispersed spores assigned to *Todisporites* *rotundiformis* (Malyavkina) Pocock. This distinctive species is fairly common in the Monitor Butte Member of the Chinle Formation in Petrified Forest National Park, Arizona, the Fort Wingate area of New Mexico, and the White Canyon area in southeastern Utah (Ash, 1970, 1975).

Family Matoniaceae

This living family is represented by the pedately compound leaf *Phlebopteris smithii* (Daugherty) Arnold emended Ash, et al. (1982). This fossil was assigned to the obsolete genus *Laccopteris* when it was originally described by Daugherty (1941) but later it was assigned to the correct genus *Phlebopteris* by Arnold (1947). The leaf is composed of as many as 14 pinnae that are divided into narrow, oblong pinnules with rounded apices. The pinnae arise from the upper sides of two lateral arms that develop from the top of a long petiole (Fig. 4I). Each pinnule contains a strong midrib which extends most of the way to the apex of the pinnule and then dissolves into several veins that end at the margin. Lateral veins arise alternately from the midrib and usually fork once before reaching the pinnule margin. Both fertile and sterile pinnules occur in the same pinnae. Superficial ring-like sori occur on the lower surfaces of the pinnules of this species and consist of 5-14 oval sporangia that have a vertical to slightly oblique annulus. The spores are more or less triangular and trilete in polar view and according to Litwin (1984) are most similar to the dispersed spore species *Dictyophyllidites harrisii* Couper and *D. mortonii* Playford and Dettman. The remains of this species are very common in the Monitor Butte Member of the Chinle Formation in Petrified Forest National Park, Arizona, near Fort Wingate, New Mexico, in the White Canyon and Lake Powell areas of southeastern Utah (Arnold, 1956, Ash, 1975). It is also found in the Dockum Group of Late Triassic age in west Texas near Amarillo. Living members of this family are found in the humid monsoonal tropics of Southeast Asia.

Family Dipteridaceae

Clathropteris walkerii Daugherty emend. Ash (1970) is the only representative of this living family known in the park. It is a large palmate leaf up to 30 cm in diameter consisting of six to ten linear-lanceolate pinnae spreading outward from a broad basal web (Fig. 4J). The pinnae are up to 12 cm long and 3 cm wide and have acute apices. Numerous, short, acutely pointed, forward directed teeth are present along the pinnae margins. The leaf has net venation with many blind vein endings. Sori are irregularly distributed on the lower surfaces of the fertile leaves and consist of a round mass of 7-9 spherical sporangia which have complete oblique annulii. The spores of this species are rounded triangular in polar view and reportedly (Litwin, 1984) are most similar to the dispersed spore species *Granulatisporites infirmus* (Balme) Cornet and Traverse.

This species has been found in the Monitor Butte Member of the Chinle Formation in Petrified Forest National Park, in the Fort Wingate area of New Mexico and the White Canyon area in southeastern Utah as well as in the Dockum Group near Amarillo in west Texas (Ash, 1970; 1972c). Living members of this family inhabit the humid monsoonal tropics of Southeast Asia.

Family Uncertain

A few species of fern-like leaves that can not be assigned to a particular family of ferns because their fertile structures are not known occur in the Chinle Formation in Petrified Forest National Park. It is possible that some of these fossils are in fact the leaves of pteridosperms (commonly called seed ferns), a group of extinct plants that had fern-like leaves but reproduced by means of seeds, not spores. By convention fern-like leaves are usually treated as ferns until additional information is forthcoming.

One of the most common of the fern-like leaves in Petrified Forest National Park is assigned to *Cladophlebis daughertyi* Ash (1970). It is a fairly large bipinnate leaf which when complete was about 30 cm wide and probably 60 cm or more in length when alive. The pinnules are small (typically 2 mm x 4.5 mm), delicate and somewhat falcate in outline with smooth margins (Fig. 4A). Each pinnule contains a midrib from which narrow lateral veins arise in an alternate manner Fig. 4B). *Cladophlebis daughertyi* occurs in the Monitor Butte Member of the Chinle Formation in Petrified Forest National Park and the Fort Wingate area of New Mexico.

A second species of *Cladophlebis*, *C. yazzia* Ash (1973), has been described also from the Petrified Forest where it is represented by just a few small fragments. The species is somewhat similar to *C. daughertyi* but the leaf is only about 5 cm wide and the pinnules are typically long and falcate with dentate margins particularly in the upper parts (Fig. 4G). Each pinnule contains a midrib from which narrow lateral veins arise in an alternate manner.

Sphenopteris arizonica Daugherty emend. Ash (1999) is the third fern-like leaf to have been described from the park. The leaves that have been found are about 10 cm wide and 40 cm long. They are tripinnate below becoming bipinnate above. The ultimate segments (pinnules) are oval to lobed and range up to 6 mm tall and 4 mm wide (Fig. 4C). There is the possibility that these leaves actually are parts of a large bipartite leaf. If this were to be confirmed it would indicate that *S. arizonica* is a seed fern as are at least some of the other fossils referred to the genus. The pinnules on some of the leaves attributed to this species show evidence of having provided nourishment for phytophagous insects (Ash, 1999). The evidence is similar to that reported on the fern *Cynepteris lasiophora* and demonstrates that the feeding occurred while the leaves were alive and still attached to the parent plant.

Marcouia neuropteroides (Daugherty) Ash is another example of a fern-like frond found in the Chinle Formation in Petrified Forest National Park and elsewhere in the Colorado Plateau region. This leaf is a palmately compound leaf that was perhaps as large as one meter in diameter according to Daugherty (1941). The pinnae are linear-lanceolate and are divided into oval to linear pinnules which have wavy to lobed margins (Fig. 4D). Numerous lateral veins arise from the pinnule midrib at a high angle and divide and anastomose one or more times with adjacent veins. Usually the anastomosing takes place near the margins and the lateral veins are rarely free at the margins. Originally Daugherty (1941) attributed this species to the genus *Ctenis* but that assignment was found unacceptable by Ash (1972d) and the fossil was reassigned to the new genus *Marcouia*. Small oval holes found in several of the pinnules of *M. neuropteroides* appear to have been caused by phytophagous insects (Ash, 1997).

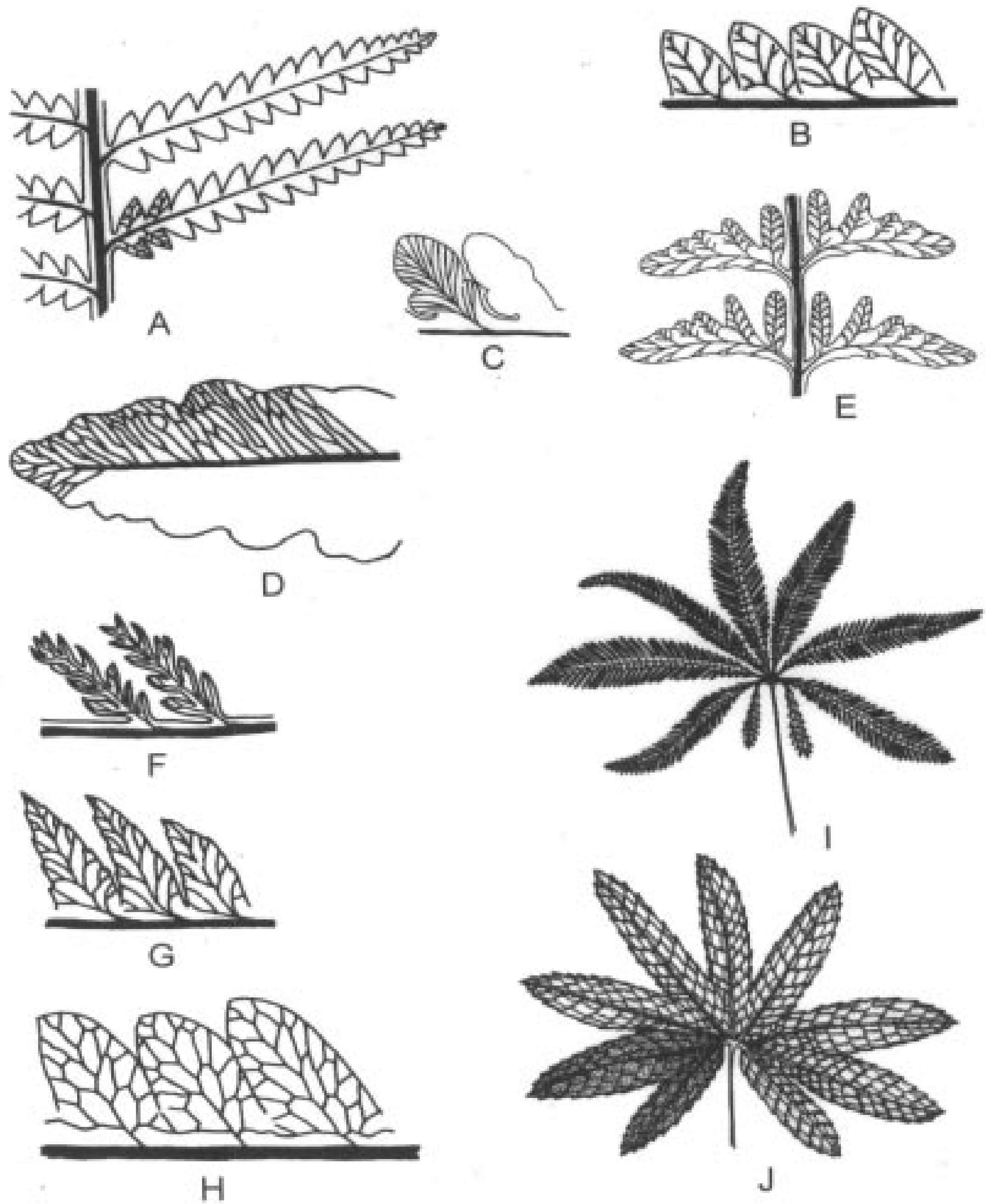


FIGURE 4. Sketches of the pinnules, venation, and morphology of the fern leaves (E-F, H-J) and the fern-like fronds (A-D, G) found in the Chinle Formation. A,B, *Cladophlebis daughertyi*. C, *Sphenopteris arizonica*. D, *Marcouia neuropteroides*. E, *Todites fragilis*. F, *Wingatea plumosa.* G, Cladophlebis yazzia. H, Cynepteris lasiophora. I, Phlebopteris smithii. J, Clathropteris walkerii. (A, D, x1 1/2; B, C, F, G, H, x3; E, I, J, x1/4) Adapted from several sources including Ash, 1970, 1972a, d, 1973, 1980, 1999.

PALEOCLIMATOLOGICAL IMPLICATIONS

Of all the fossil plants found in the lower part of the Chinle Formation, the ferns seem to be particularly useful for reconstructing the climate under which it was deposited. Such reconstruction using fossil ferns and/or other plants is based on two assumptions: first, that the climatic preferences of fossil plants were similar to that of their nearest living relatives and second that the morphological features of fossil species are similar to those of extant plants inhabiting a particular existing climate.

Before discussing the paleoecological implications of the Chinle ferns it should be noted that most (about 80%) living ferns are restricted to the tropics and subtropics where the regional climate ranges from consistently wet to monsoonal (Lellinger, 1985). In those regions, the climate is humid throughout the year, although it may be slightly less so during the dry part of the monsoonal cycle. Also, it should be noted that the uplands in those regions are as humid as the river valleys, if not more so (Tryon, 1986). The relatively specialized, so called desert ferns live in more arid areas, but they are easily distinguished from the more common ferns that inhabit the humid tropics and subtropics.

The nearest living relatives of all the Chinle ferns live in the humid tropics and subtropics. Two of them, *Clathropteris walkerii* and *Phlebopteris smithii*, belong to families that formerly had a worldwide distribution (Tidwell and Ash, 1995) but now only occur in areas of southeast Asia that have a monsoonal climate (Bower, 1928). The other Chinle ferns are not as closely related to any living ferns but nevertheless their relatives always inhabit the humid tropics and subtropics where some may even live under a monsoon climate. None of the Chinle ferns are at all closely related to the desert ferns.

The morphological features of the Chinle ferns are comparable to those of ferns that now live in consistently wet to monsoonal tropical to subtropical climates. Just like their living counterparts from those climatic regimes, the Chinle ferns have superficial, unprotected stomata on both sides of the leaves. The leaves of most, including *Todites fragilis, Cynepteris lasiophora*, and *Wingatea plumosa* as well as the two species of *Cladophlebis* were originally thin and delicate. These ferns, like their living counterparts, probably inhabited shady areas under larger plants such as cycadophytes and conifers and perhaps other ferns such *Phlebopteris smithii* and *Clathropteris walkerii*, which had somewhat more robust leaves. These latter two ferns, just like their nearest living relatives, probably lived in an open environment and provided shelter for the more delicate ferns and other plants, as is characteristic of their descendants in the monsoonal tropics (Bower, 1928).

The Chinle ferns have none of the special morphological adaptations that permit ferns to survive in areas where the water supply is severely limited. For example, the leaves in the Chinle ferns are generally broad (always narrow in desert ferns) and remain flat (curl up when the weather gets extremely dry in desert ferns), and the stomata in the Chinle ferns occur on both sides of the leaves (restricted to the lower side in desert ferns) and are virtually unprotected (protected by hairs and scales in desert ferns). A desert fern that shares these later characters is *Notholaena parryi*. It inhabits the Colorado Desert and has small leaves that curl up

TABLE 1. Key to the fern leaves and fern-like foliage of the Chinle Formation. The morphology and venation of the leaves are used in this key to differentiate the species illustrated in Figure 4.

1. Leaf palmate	2
1. Pinnae margins toothed	*Clathropteris walkerii*
2. Pinnae margins wavy to lobed	*Marcouia neuropteroides*
1. Leaf not palmate	2
2. Leaf pedate	*Phlebopteris smithii*
2. Leaf pinnate	3
3. Venation reticulate	*Cynepteris lasiophora*
3. Venation not reticulate (open)	4
4. Pinnules rounded	5
5. Basiscopic pinnules fused	*Todites fragilis*
5. Basiscopic pinnules not fused	*Sphenopteris arizonica*
4. Pinnules not rounded (angular)	5
5. Pinnules narrow	*Wingatea plumosa*
5. Pinnules not narrow (broad)	6
6. Pinnule margins toothed	*Cladophlebis yazzia*
6. Pinnule margins not toothed (smooth)	*C. daughertyi*

when the weather becomes extremely dry. Nearly all of the stomata occur on the lower surface of the leaves in this species and they are protected by hairs and scales (Helvy, 1963). Similar characters also are present in the several species of the desert fern *Cheilanthes* which inhabit the arid parts of India (Nayar (1962) and elsewhere (Marsh, 1914).

The morphology and nearest living relatives of many of the non-fern species found in the Chinle Formation indicate that they too lived under a regional humid tropical to subtropical climate. Although most of them obviously lived along streams and around lakes, a few obviously were transported some distance from uplands to where they were deposited, and provide data on the paleoclimate of those areas. Particularly instructive in this respect are the compressions of leaf shoots and isolated leaves of the conifers in the flora. They are generally rare and fragmentary, indicating that they were transported some distance before burial. These fossils do not have the epidermal features that are said (Parrish, 1998) to be indicative of a strongly arid climate, such as deeply sunken, strongly protected stomata, stomata in grooves, exceedingly thick cuticles, or stomatal plugs. Rather, their epidermal features are close to those of the plants, including the ferns, of the contemporary riparian communities, indicating that they too inhabited a similar climate. Thus, when all of the evidence provided by the plants is considered it is apparent that both the riparian and upland communities lived under a humid subtropical to tropical climate that could have been monsoonal or consistently wet.

In conclusion, the theory of Demko, et al. (1998) that the ferns and other compressed plant fossils in the lower part of the Chinle Formation reflect only the humid climate along streams and around lakes and not the climate of the surrounding region ignores important facts. First, the climate along modern rivers is little different than that of the region they pass through and this was most probably true in the past. Second, humid climates simply could not and do not exist in narrow corridors along water courses or around lakes under an otherwise arid or strongly seasonal climate as visualized by Demko, et al. (1998). Although large trees may grow along the banks of some rivers in arid regions such as the Sonoran Desert the climate along such corridors is closely similar to that of the surrounding region and the trees obtain water from the water table. Furthermore, ferns can not and do not survive along the Rio Grande, the Colorado, the Nile, the Darling, and other rivers passing through arid lands. Not even desert ferns live along the water courses. Instead they inhabit certain specialized microhabitats. For example, the desert fern *Notholaena parryi* typically grows in crevices and under rocks in the Colorado desert (Nobel, 1978) and *Cheilanthes mysurensis* and related species grow on gravelly or rocky substrata in the deserts of India (Nayar, 1962).

CONCLUSIONS

Ten species of ferns and fern-like fronds are now known from the lower part of the Chinle Formation in Petrified Forest National Park and elsewhere in the southwestern United States. The ferns represent nearly one-fifth of the plant species based on megafossils in the Chinle flora and are assigned to four living and two extinct families; several are unassigned. Using both their morphology and the climatic preferences of their nearest living relatives it is evident that the Chinle ferns lived under a humid subtropical to tropical climate. The climate could very well have been monsoonal since the nearest living relatives of two of the ferns now inhabit monsoonal southeast Asia and more distant relatives of the other ferns also live there, in addition to other parts of the tropics. These conclusions are also corroborated by many of the other plant fossils found in the Chinle Formation in the park and elsewhere.

ACKNOWLEDGEMENTS

I acknowledge with thanks all of the support I have received over the years from the superintendents and staff of Petrified Forest National Park. Also, I am grateful to the Petrified Forest Museum Association for financial support

REFERENCES

Arnold, C.A., 1947. An introduction to paleobotany. New York, McGraw-Hill Book Co., 433 p.

____, 1956. Fossil ferns of the Matoniaceae from North America: Journal of the Palaeontological Society of India, 1: 118-121.

Ash, S.R., 1970. Ferns from the Chinle Formation (Upper Triassic) in the Fort Wingate area, New Mexico. U. S. Geological Survey Professional Paper 613-D: 1-40.

____, 1972a. Plant megafossils of the Chinle Formation, *in,* W.J. Breed and C.S. Breed, (eds), Investigations in the Triassic Chinle Formation. Museum Northern Arizona Bulletin, 47: 23-43.

____, 1972b. The search for plant fossils in the Chinle Formation, *in,* W.J. Breed and C.S. Breed, (eds), Investigations in the Triassic Chinle Formation. Museum Northern Arizona Bulletin 47: 45-58.

____, 1972c. Upper Triassic Dockum flora of eastern New Mexico and Texas. New Mexico Geological Society, 23rd Annual Field Conference, east-central New Mexico, Guidebook, p. 124-127.

____, 1972d. *Marcouia* gen. nov., a problematical plant from the Late Triassic of the southwestern U.S.A. Palaeontology, 15: 423-429.

____, 1973. Two new Late Triassic plants from the Petrified Forest of Arizona. Journal of Paleontology, 47: 46-53.

____, 1975. The Chinle (Upper Triassic) flora of southeastern Utah. Four Corners Geological Society Guidebook, 8th Annual Field Conference, Canyonlands, p. 143-147.

____, 1980, Upper Triassic floral zones of North America, *in,* D.L. Dilcher and T.M. Taylor, (eds), Biostratigraphy of fossil plants. Dowden, Hutchinson and Ross, Inc., Stroudsburg, PA., p. 153-270.

____, 1987. Petrified Forest National Park, Arizona, *in,* S. S. Beus, (ed), Centennial Field Guide, Volume 2, Rocky Mountain Section of the Geological Society of America, p. 405-410.

____, 1989. A catalog of Upper Triassic plant megafossils of the western United States through 1988, *in,* S.G. Lucas and A.P. Hunt, (eds), Dawn of the Age of Dinosaurs in the American Southwest. New Mexico Museum of Natural History, Albuquerque, p. 189-222.

____, 1994. *Donwelliacaulis chlouberii* gen. et sp. nov. (Guaireaceae, Osmundales) one of the oldest Mesozoic plant megafossils in North America. Palaeontographica, 234B:1-17.

____, 1997. Evidence of arthropod-plant interactions in the Upper Triassic of the southwestern United States. Lethaia, 29: 237-248.

____, 1999. An Upper Triassic *Sphenopteris* showing evidence of insect predation from Petrified Forest National Park, Arizona. International Journal of Plant Sciences, 160: 208-215.

____, 2000. Evidence of oribatid mite herbivory in the stem of a Late Triassic tree fern from Arizona. Journal of Paleontology, 74: 1065-1071.

____ and G. Creber, 1992. Palaeoclimatic interpretation of the wood structures of the trees in the Chinle Formation (Upper Triassic) in the area of Petrified Forest National Park, Arizona, U.S.A. Palaeogeography, Palaeoclimatology, Palaeoecology, 96: 299-317.

____, R. Litwin, and A. Traverse, 1982. The Upper Triassic fern *Phlebopteris smithii* (Daugherty) Arnold and its spores. Palynology, 6: 203-219.

Blakey, R.C., 1989. Triassic and Jurassic geology of the southern Colorado Plateau, *in*, J.P. Jenny, S.J. Reynolds, (eds), Geologic evolution of Arizona. Arizona Geological Society Digest, 17: 369-396.

Bower, F.O., 1928. The ferns (Filicales), Volume III. The Leptosporangiate ferns. Cambridge University Press, Cambridge. 306 p.

Daugherty, L.H., 1941. The Upper Triassic flora of Arizona. Carnegie Institution of Washington Publication, 526:1-108.

____, 1960. *Itopsidema*, a new genus of the Osmundaceae from the Triassic of Arizona. American Journal of Botany, 47: 771-777.

Demko, T.M., R.F. Dubiel,and J.T. Parrish, 1998. Plant taphonomy in incised valleys: Implications for interpreting paleoclimate from fossil plants. Geology, 26: 1119-1122.

Dubiel, R.F., S.T. Hasiotis, and T.M. Demko, 1999. Incised valley fills in the lower part of the Chinle Formation, Petrified Forest National Park, Arizona: Complete measured sections and regional stratigraphic implications of Upper Triassic rocks, *in,* V.L. Santucci and L. McCelland, (eds), National Park Service Paleontological Research, 4: 78-84.

Helvy, R.H., 1963. Adaptations of cheilanthoid ferns to desert environments. Journal of the Arizona Academy of Sciences, 2: 164-175.

Lellinger, D.B., 1985. A field guide of the fern and fern-allies of the United States and Canada. Smithsonian Institution Press, Washington, D.C. 389 p.

Litwin, R.J., 1984. Fertile organs and in situ spores of ferns from the Late Triassic Chinle Formation of Arizona and New Mexico, with discussions of associated dispersed spores: Review of Palaeobotany and Palynology, 42:101-146.

____, 1986. The palynostratigraphy and age of the Chinle and Moenave Formations, southwestern U.S.A. PhD thesis, Pennsylvania State University, 256 p.

____, A. Traverse and S.R. Ash, 1992. Preliminary palynological zonation of the Chinle Formation, southwestern U. S. A., and its correlation with the Newark Supergroup (eastern U. S. A.). Review of Palaeobotany and Palynology, 68: 269-287.

Marsh, A.S., 1914. The anatomy of some xerophilous species of *Cheilanthes* and *Pellaea*. Annals of Botany, 28: 671-684.

Nayar, B.K., 1962. The morphology of some species of *Cheilanthes.* Journal of the Linnean Society (Botany), 58: 449-460.

Nobel, P.S., 1978. Microhabitat, water relations, and photosynthesis of a desert fern, *Notholaena parryi*. Oecologia, 31: 293-309.

Parrish, J.T., 1998. Interpreting pre-Quaternary climate from the geologic record. Columbia University Press, New York City. 338 p.

Stewart, J.H., F.G. Poole, and R.F. Wilson, *with a section on* Sedimentary petrology *by* R.A. Cadigan, *and a section on* Conglomerate studies *by* W. Thordarson, H.F. Albee, and J.H. Stewart, 1972. Stratigraphy and origin of the Chinle Formation and related Upper Triassic strata in the Colorado Plateau region. U.S. Geological Survey Professional Paper, 690:1-336.

Tidwell, W.D. and S.R. Ash, 1995. A review of selected Triassic to Early Cretaceous ferns. Journal of Plant Research, 107: 417-442.

Tryon, R.M., 1982. Pteridophytes, *in,* H. Leith and M.J. H. Werger (eds), Tropical Rain Forests of the world. Ecoobelsystems of the world, v. 14B. Elsevier, Amsterdam. 346 p.

____, 1986. The biogeography of species, with special reference to ferns. Botanical Review, 52:117-155.

PALEONTOLOGY OF THE K/T BOUNDARY INTERVAL: BADLANDS NATIONAL PARK, SOUTH DAKOTA

JOHN A. CHAMBERLAIN, JR.[1], DENNIS O. TERRY, JR.[2], PHILIP W. STOFFER[3], MARTIN A. BECKER[4]
[1]Department of Geology, Brooklyn College, Brooklyn, NY 11210
[2]Department of Geology, Temple University, Philadelphia, PA 19122
[3]U. S. Geological Survey Library, Menlo Park, CA 94025
[4]Department of Physics & Geology, The College of New Jersey, Ewing, NJ 08628

ABSTRACT—We have documented a distinctive zone of disrupted sediments over 300 km^2 in the Badlands area of South Dakota. This Disrupted Zone (DZ) is located in the Maastrichtian Fox Hills Formation about 20 meters above its transitional contact with the Pierre Shale, and ranges from 0.5 to 5 meters in thickness. Based on Sr age dates, sedimentary features, and impact ejecta, we interpret the DZ as a distal manifestation of the end-Cretaceous Chicxulub Impact Event. The DZ occurs in an interval with uncommon, but significant fossil content. Scaphitid ammonites characteristic of the *Jeletzkytes nebrascensis* ammonite zone occur below and within the DZ, but not above it. In addition, the sections, including the DZ itself, contain nuculid and inoceramid bivalves, osteichthian and chondrichthian remains, crustacean crawling traces, leaf fragments, and disseminated, and sometimes carbonized, plant debris. Compared to earlier late Cretaceous faunas of the Western Interior, the Badlands K/T fauna is impoverished in that it contains relatively few species. This impoverishment is unrelated to the end-K impact, and is more likely the result of environmental conditions in the Seaway coupled with the high-stress conditions of local environments within which the Badlands fauna lived.

INTRODUCTION

During late Cretaceous time the Western Interior Sea way, an epeiric sea of considerable extent, covered much of the mid-continent region of North America. Kennedy et al. (1998) suggest that during the *Jeletzkytes nebrascensis* zone of the Late Maastrichtian the Seaway extended northward from the Cretaceous Gulf of Mexico to North Dakota (Figure 1). However, the absence of marine sections that can be unequivocally dated to the latest Maastrichtian or to the Cretaceous/Tertiary transition (e.g. Obradovich, 1993) has generally been interpreted to mean that the Seaway had retreated completely from the northern plains region of the United States by the end of the Cretaceous. In this scenario, marine rocks of early Tertiary age, the Cannonball Formation for example, necessarily imply the temporary return of marine conditions during the early Tertiary.

The late Cretaceous succession exposed in and near Badlands National Park in southwestern South Dakota contains evidence that challenges this view. In two recent papers (Stoffer et al. 2001; Terry et al., in review), we describe a zone of distorted bedding in the marine rocks of the Badlands area (referred to here as the DZ) which resembles the highly contorted, chaotic bedding seen in some Gulf of Mexico K/T boundary sections (summarized in Smit et al. 1996). Moreover, the Badlands DZ interval contains impact ejecta and fossil occurrences which suggest association with biotic and geologic events that mark the end of the Cretaceous. The Badlands DZ is conformably overlain by a considerable thickness of what thus would be earliest Paleocene marine sediments. In suggesting continuous marine deposition across the K/T boundary in the Badlands area, this interpretation implies that the Seaway had not disappeared from the northern plains at the end of the Cretaceous, but was a

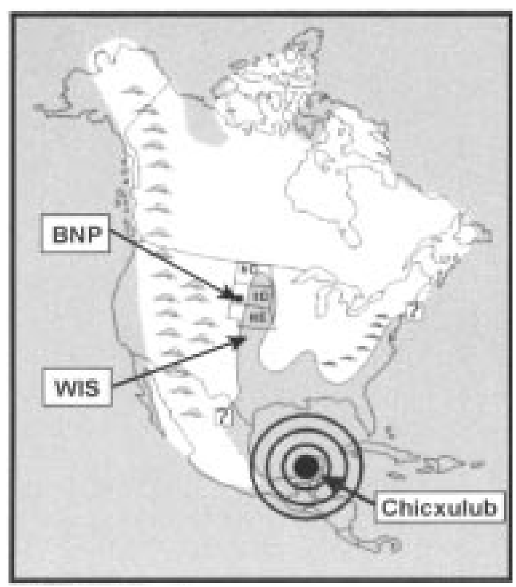


FIGURE 1. Paleogeography of North America at the end of the Cretaceous Period based on recent ammonite biostratigraphy. WIS – Western Interior Seaway. BNP – Badlands National Park. Modified from Fig. 1 of Terry et al. (in review). Paleogeographic data from Kennedy et al. (1998).

significant paleogeographic feature in this area well into the Paleocene.

In Stoffer et al. (2001), we were primarily interested in describing the Late Cretaceous biostratigraphic framework of the Badlands, within which this K/T boundary interval occurs. In Terry et al. (in review) we focused on the physical and sedimentological evidence suggesting that this distinctive zone of disrupted bedding does indeed mark the K/T boundary. In the present paper we focus on the paleontologic character of this marine K/T boundary interval, and in what the fossils indicate regarding the paleoenvironmental conditions in the Badlands region at the end of the Cretaceous.

REGIONAL GEOLOGY

The Late Cretaceous stratigraphic record of the Western Interior Seaway consists of two marine units in the northern Great Plains: the Pierre Shale and Fox Hills Formation. The Pierre Shale is a fossiliferous, gray mudstone, locally calcareous, and is generally interpreted as the product of deposition in the distal, central part of the Seaway. The overlying Fox Hills Formation, also fossiliferous, is a regressive phase of sedimentation that tracked the retreat of the Western Interior Seaway at the end of the Cretaceous Period. It consists predominately of buff colored sands and silts, and is interpreted as the product of deposition in a littoral to sub-littoral near-shore setting. The biostratigraphy of these units is based heavily on the molluscan zonation for the upper Cretaceous established by earlier workers (Gill & Cobban, 1966; Waage, 1968; Speden, 1970; Kaufmann, 1977), and summarized in recent reviews by Kaufmann et al. (1993) and Cobban (1993).

In the Badlands National Park region, Tertiary pedogenesis has severely altered the underlying Cretaceous units (Retallack, 1983; Terry & Evans, 1994), making them difficult to recognize and degrading or destroying much of their original fossil content. As a result of these conditions, the Upper Cretaceous biostratigraphic framework for the northern Great Plains is based largely on exposures in such areas as the Missouri, Moreau, and Grand River valleys of central South Dakota, and the Old Woman anticline of eastern Wyoming, rather than on exposures in the Badlands region. However, our recent biostratigraphic work on Upper Cretaceous strata in Badlands National Park shows that the stratigraphy of these units in southwestern South Dakota correlates with better known areas to the east and west (Stoffer, 1998; Stoffer et al., 1998; Stoffer et al. 2001). In this work, we have established on the basis of stratigraphic and paleontologic evidence that although the Pierre Shale and Fox Hills Formation are considerably thinner in the Badlands than elsewhere, the normal sequence of Western Interior ammonite range zones is preserved.

GEOLOGY OF THE BADLANDS K/T BOUNDARY

During our initial investigations we discovered a zone of highly contorted bedding in the brightly colored rocks of the "Interior Zone" below the Tertiary White River Group (Stoffer et al. 1997). This disrupted zone (DZ) occurs in what we established on sedimentologic and paleontologic grounds as pedogenically altered, marine Fox Hills Formation (Stoffer et al. 1997; Stoffer 1998; Stoffer et al. 1998). Further investigation of the DZ indicates that it marks the K/T boundary in this region, and represents seismically induced slumping and liquefaction of unconsolidated nearshore sediments derived from the effects of shock waves emanating from the Chicxulub impact (Stoffer et al. 2001; Terry et al., in review).

The Badlands DZ is clearly an unusual feature as it is the only zone of distorted, convoluted bedding anywhere in the Upper Cretaceous beds of southwestern South Dakota (Stoffer et al., 1997). The DZ thus seems to mark the occurrence of some unusual late Cretaceous event. We argue from the following considerations, discussed in Stoffer et al. 2001, and Terry et al., in review, that this event is indeed the end-K Chicxulub impact:

- The DZ is directly overlain by a dark colored mudstone containing impact microspherules.
- $^{87}Sr/^{86}Sr$ age dates on belemnites collected from 1 to 3 m below the DZ yield an average age of 67.6 Ma (n=10). This shows that the DZ is latest Maastrichtian in age, and is too young to be derived from the Campanian (74 Ma) Manson impact discussed by Izett et al. (1998).
- The DZ contains macrofossils characteristic of the late Maastrichtian *Jeletzkytes nebrascensis* ammonite zone and pollen characteristic of the latest Maastrichtian *Wodehouseia spinata* palynostratigraphic zone.
- The DZ occurs in the Enning facies described by Pettyjohn (1967) as the stratigraphically highest part of the Fox Hills Formation, roughly equivalent in age to the terrestrial Hell Creek Formation elsewhere in South Dakota.
- The E/W orientation of the liquefaction features in the DZ indicates that the energy source for the deformation was located nearly due south of the Badlands, i.e. in the direction of Chicxulub (Figure 1).

DISRUPTED ZONE LOCALITIES : SEDIMENTOLOGY AND FOSSIL PRESERVATION

Our paleontologic reconstructions are based on three main outcrops of the DZ within the study area: Wilderness Access Trailhead (WATH), and Dillon Pass (DP), both in Badlands National Park, and Creighton (CR), about 50 km north of the Park (Figure 2). Each location has a unique combination of paleontological characteristics that provide insight into the nature of the fauna inhabiting the Western Interior Seaway during the K/T transition. Sage Creek Basin (SCB), also within Badlands National Park, provides additional information on DZ fossils. The stratigraphy and sedimentology of these sites is discussed more fully in Stoffer et al. (2001) and Terry et al. (in review).

Creighton

The DZ exposure at Creighton, SD, is located in Section 27, T3N, R15E, on a gravel road about 10 km west of its intersection with Creighton Road. The exposure lies at the head of a gully just below the crest of the Cheyenne River Breaks. The Fox Hills Formation at Creighton is about 45 meters thick, and is composed of cross bedded sands and silts, ripple laminated silts, and herring bone cross stratification with an overall southeast flow direction. The DZ lies approximately 20 meters above the base of the gradational lower contact with the Pierre Shale. The DZ is 0.5 to 1 meter thick and is bounded above and below by undisturbed sediments. The main body of the DZ is composed of a singular, predominantly massive, but occasionally coherent, body of beige fine sand and silt (Figure 3). Internally, the sand preserves slump/roll structures and isolated 1 to 10 cm blocks of sediment with cross stratification.

Of the DZ sites so far discovered, Creighton has the best fossil preservation and the greatest biotic diversity. Invertebrate and vertebrate remains, as well as plant material, are found below, above, and within the DZ (Figure 3), but they become rarer with distance above the DZ, and, with exception of plant debris, all but disappear several meters above this horizon. Fossils are not clustered in concretions as is commonly the case among Cretaceous Western Interior Seaway units. Instead, fossils occur in small pockets of shell debris or as isolated, and often fragmentary skeletal elements. Original shell carbonate is present in some specimens, although such material is invariably chalky and friable rather than pristine. Many specimens are preserved as casts and molds, some of which are sharp and well defined. Plant fossils occur as lenses of amorphous, sometimes carbonized, debris with occasional larger leaf or twig fragments also present.

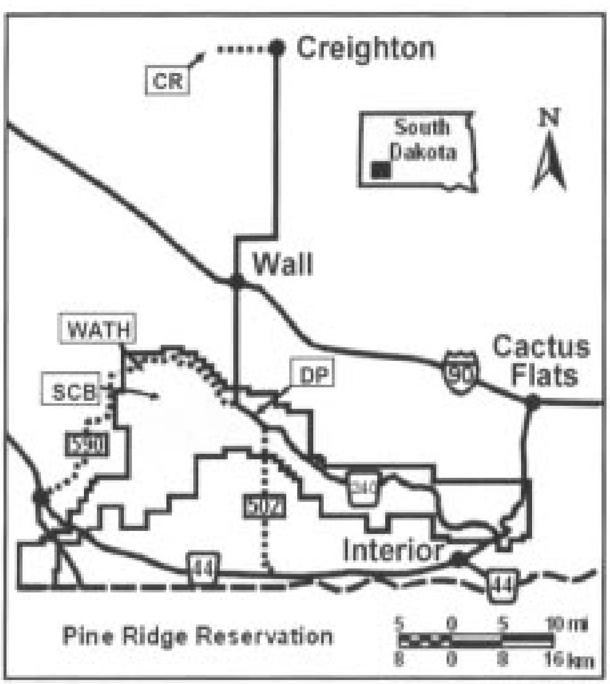


FIGURE 2. Map of the Badlands National Park (BNP) area showing locations of the K/T boundary sections discussed here. BNP in gray. CR - Creighton; DP - Dillon Pass; GTO - Grassy Tables Overlook; SCB – Sage Creek Basin; and WATH - Wilderness Access Trailhead.

Dillon Pass

The DZ at Dillon Pass is visible to the east of SD Rte240 as the highway descends from the Pinnacles to the base of Dillon Pass along the headwaters of Conata Creek. The outcrop discussed here is exposed in a steep arroyo cut by a tributary of Conata Creek on the west side of the highway in Section 20, T2S, R16E. At this locality the K/T boundary interval lies within the Fox Hills Formation, which at this site, as throughout Badlands National Park, comprises the lower part of the brightly colored, pedogenically altered Interior Zone. The base of the exposed section is marked by a massive pale yellow sandy silt that becomes glauconitic and then red in color at the top (Figure 4). The DZ overlies this siltstone, and is composed of 4.5 to 5 meters of massive to convoluted clayey sandstone and siltstone with occasional beds of resistant and convoluted sandstone (Figure 4). Directly above the DZ are undisturbed, unfossiliferous laminated mudstones, the first of which contains impact spherules. The first nonmarine sediments, the mudstones of the late Eocene Chamberlain Pass Formation, lie four meters above the top of the DZ.

Invertebrate, vertebrate, and plant fossils occur at Dillon Pass, but they are much less abundant than at Creighton. Most invertebrate fossils occur as isolated, and often fragmentary, molds and casts. None contain original shell material, although shell impressions sometimes show a thin, friable limonitic coating, often with traces of original shell ornamentation, which probably represents the remnants of geochemically altered and leached shell carbonate. Finely disseminated plant debris is also present. The fossils occur in the reddish to pale yellow siltstone directly below the DZ (Figure 4), and appear to be concentrated about 20-40 cm beneath the base of the DZ. They do not appear to extend below a thin band of lenticular concretions, visible in Figure 4, about 50 cm beneath the DZ. Unlike Creighton, no fossils have been found in the DZ itself. This situation may reflect leaching of original shell carbonate which occurred during the pedogenic alteration of the Dillon Pass section (Retallack, 1983; Terry and Evans, 1994). The geochemical effects of pedogenesis appear to diminish downward in the Dillon Pass section. Thus, organic remains high in the section, above and within the DZ, were probably obliterated, while those lower in the section, below the DZ, were degraded but not totally destroyed.

Wilderness Access Trailhead

The DZ at this locality is located in Section 3, T2S, R15E about 0.5 km south of the Wilderness Access Trailhead parking area on Sage Rim Road. It can be accessed from a bison trail leading southward from the parking area. The DZ lies within the Fox Hills Formation and is about 5 m above the contact with the underlying Elk Butte Member of the Pierre Shale. As at Dillon Pass, and generally in Badlands National Park, the DZ interval lies within the brightly colored Interior Zone of Tertiary pedogenic alteration. The DZ is about 0.5 m thick at this site and is marked by convoluted sandy beds (Figure 5). At the base of the DZ is a thin, but distinct sheet

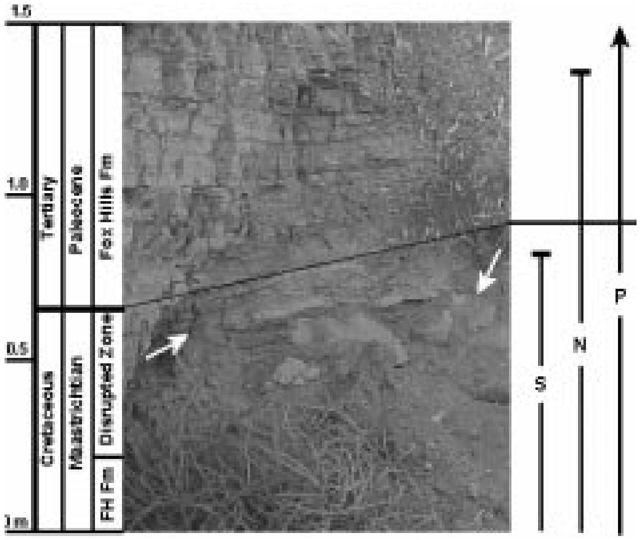


FIGURE 3. Fossil occurrences in K/T boundary interval at Creighton, SD. The K/T boundary lies at the top of the Disrupted Zone (DZ). White arrows show deformed sandy beds within the DZ. Vertical lines at right show stratigraphic ranges of common macrofossil groups at Creighton: S – scaphitid ammonites; N – nuculid bivalves; P – leaf fragments and disseminated plant debris.

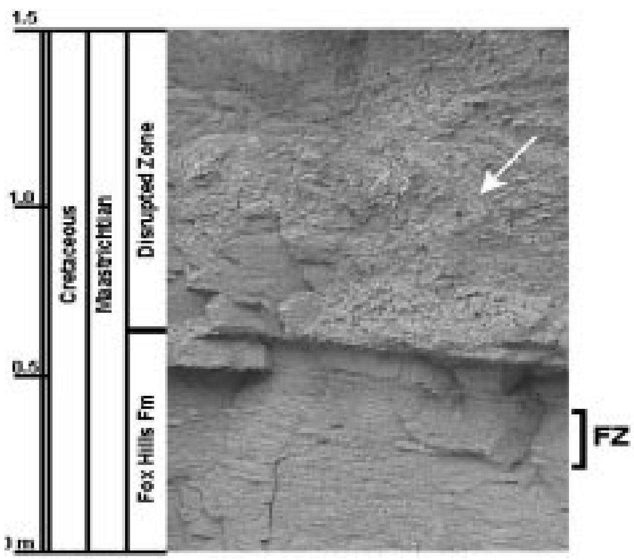


FIGURE 4: Fossil occurrences in the K/T boundary interval, Dillon Pass, BNP. The figure shows only the lower portion of the Disrupted Zone (DZ) and the beds immediately below it. White arrow shows deformed sandy beds within the DZ. FZ – zone containing nuculid bivalves, rare scaphitid ammonites, and disseminated plant debris, with lenticular, unfossiliferous concretions at base.

of laminated sand, the base of which contains flute casts and drag marks indicating a southerly sediment transport direction. Directly beneath this sand sheet is a fine glauconitic siltstone, reddish at the top, which extends to the base of the outcrop. About 50 cm below the DZ is a thin horizon of lenticular, unfossiliferous ironstone concretions. The pre-DZ bedding sequence is thus similar to that occurring beneath the DZ at Dillon Pass. At the top of the DZ lies a second sand sheet, above which is a series of drab colored sand/shale couplets extending to the top of the outcrop. These beds become sandier upward. The base of the Chamberlain Pass Formation lies about 8 m above the DZ at the Wilderness Access Trailhead site.

Invertebrate and vertebrate fossils are preserved at Wilderness Access Trailhead. They are somewhat more abundant than at Dillon Pass, but preservation of body fossils is similarly poor, with severely leached impressions of isolated, and often fragmentary, skeletal elements most commonly encountered. Plant matter is only rarely seen at WATH. Destruction of organic remains due to Tertiary paleosol development thus seems to have been even more extensive here than at Dillon Pass. As at Dillon Pass, body fossils appear to be concentrated 20 – 40 cm below the DZ (Figure 5), although belemnites occur lower still. No body fossils have yet been found within the DZ or above it at the WATH site. In contrast, trace fossils are abundant and found throughout most of the section, including the DZ.

Sage Creek Basin

Erosive down-cutting of Sage Creek and its headwaters in the interior of the Sage Creek Wilderness area of Badlands National Park has incised deeply into the upper Cretaceous units. Reconnaissance of this area reveals many exposures of the Fox Hills Formation and DZ (Stoffer et al., 2001). Although this area requires much further study, we include here preliminary observations from a cutbank of the Middle Fork of Sage Creek located in section 29, T2S, R15E. Here the Fox Hills Formation is about 8 m thick, and rests unconformably on the Elk Butte Member of the Pierre Shale. The DZ is present in these Sage Creek Basin localities and generally resembles the DZ at Wilderness Access Trailhead. The fossil content of the DZ interval also appears similar to WATH, although no detailed sampling has yet been attempted.

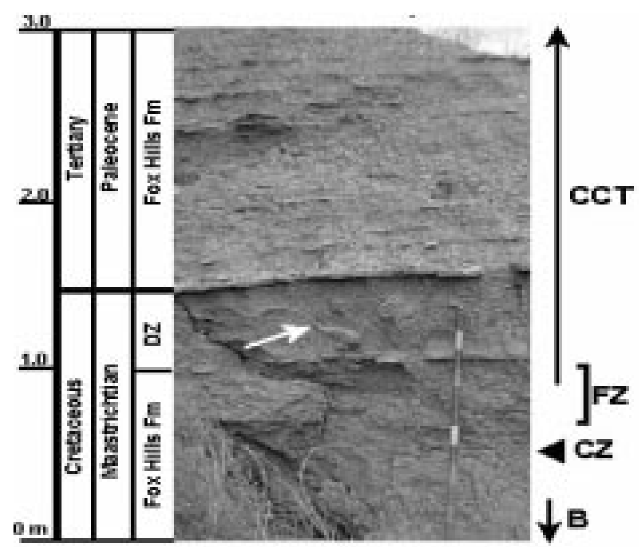


FIGURE 5. Fossil occurrences in the K/T boundary interval, Wilderness Access Trailhead, BNP. The K/T boundary lies at the top of the Disrupted Zone (DZ). White arrow shows deformed sandy bed within the DZ. FZ – zone containing bivalves, and rare osteichthian scales. CCT – crustacean crawling traces. B – belemnites.

PALEONTOLOGY OF THE DISRUPTED ZONE

Fossils described here have been deposited in the collections of the Department of Invertebrates, American Museum of Natural History (AMNH), or the Department of Geology, Brooklyn College (BC) and are identified by AMNH, and BC catalog numbers. National Park Service catalog numbers (BADL) are given for specimens collected by permit within Badlands National Park, and temporarily housed at Brooklyn College prior to permanent deposition at AMNH. Although the K/T interval contains plant fragments, pollen and dinoflagellates, we discuss macrofauna and trace fossils only in this paper. Microfossils and plants will be dealt with in a later work.

INVERTEBRATE FOSSILS

The most abundant animals preserved in the Badlands K/T boundary interval are molluscs. Two classes are present: bivalves and cephalopods. Bivalves are numerous in the K/T sections; cephalopods are rare.

Bivalves

Molluscs occur at all of the K/T sections discussed here, and at each one bivalves are numerically the most abundant fossils present. However, it is not a diverse bivalve fauna that one finds in these rocks. Only nuculids occur in significant numbers, and only in the form of one species: *Nucula cancellata* Meek & Hayden 1856. The only other bivalve we have found to date is a poorly preserved specimen of what probably is the inoceramid, *Spyridoceramus (=Tenuipteria) tegulatus* (Meek & Hayden 1856).

Nucula cancellata Meek & Hayden 1856: Speden (1970) describes three congeneric species of *Nucula* from the Fox Hills Formation in its type area north and east of the Badlands: *N. cancellata, N. planomarginata* Meek & Hayden 1856; and *N. percrassa* Conrad 1858. All three species have the equivalve, inequilateral shell form and taxodont hinge structure typical of nuculids, but *N. cancellata* differs from the other two in having prominent radial costae on the outer surface of the shell, and strong crenulations on the ventral margin of the inner shell surface. In the Badlands area specimens illustrated in Figure 6, the taxodont hinge (Figure 6A, 6B), marginal crenulations (Figure 6A, 6B) and radial costae (Figure 6C) are apparent and identify these specimens as *N. cancellata*. Although most specimens recovered from these sections are more poorly preserved (Figure 6D), and show few or no diagnostic features, it seems apparent that virtually all bivalve material in these sections derives from this species. With one possible exception, discussed immediately below, no other bivalves have been unequivocally identified.

Speden (1970) indicates that in the Fox Hills type area, *N. cancellata* occurs in the Trail City and Timber Lake members, but not in the overlying Iron Lightning Member. These members are assigned an early late Maastrichtian age (Landman & Waage 1993). Thus, the occurrence of *N. cancellata* in the earliest Paleocene beds at Creighton (Figure 3) extends the stratigraphic range of this species significantly.

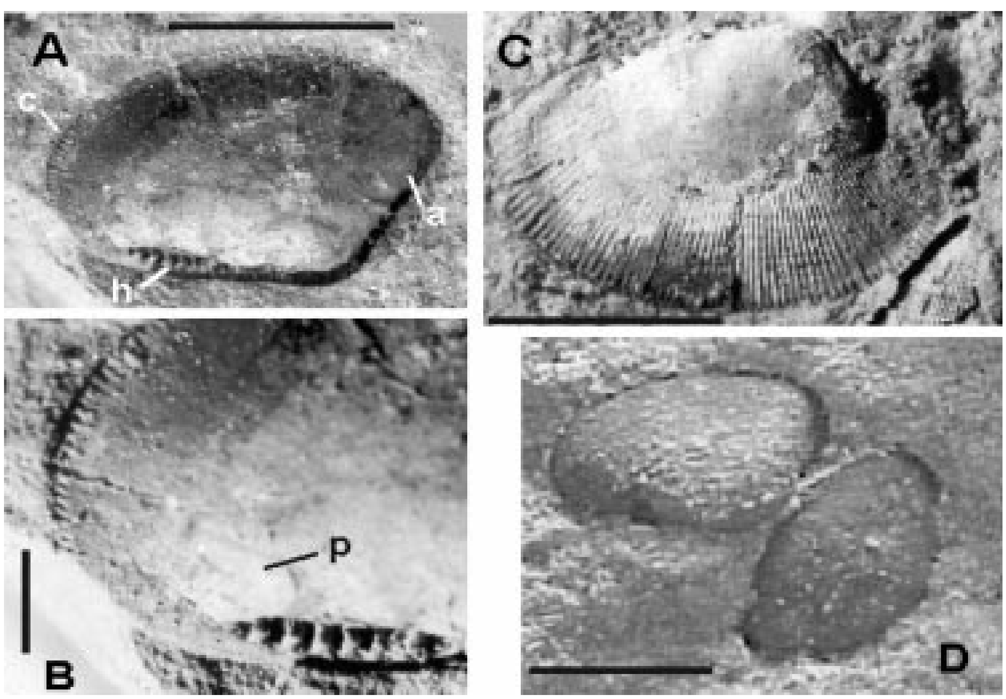


Figure 6. *Nucula cancellata.* A: AMNH-FI-46862; collected at Creighton, 20 cm below base of DZ. a – anterior adductor muscle scar; h – hinge teeth; c – crenulations on inner surface of ventral margin. Scale bar = 1 cm. B: AMNH-FI-46862; close-up of posterior margin of the shell showing hinge teeth and crenulations on the ventral margin. p – posterior adductor muscle scar. Scale bar = 0.5 cm. C: BC-CR008-00; collected within the DZ at Creighton showing radial costae on shell surface. Scale bar = 0.3 cm. D: BADL-20479, collected about 30 cm below DZ at Dillon Pass. Scale bar = 0.5 cm.

Spyridoceramus (= Tenuipteria) tegulatus (Meek & Hayden, 1856): Examination of material collected at WATH, reveals a poorly preserved, tiny fragmentary shell (Fig 7A) that closely resembles the elongate, or "eared", juvenile form of the late Maastrichtian inoceramid, *S. tegulatus* (Fig. 7B). The WATH specimen is elongate, slightly curved, and shows the concentric ornamentation characteristic of the later forms of the species. The specimen also contains packets of fibrous material oriented perpendicular to the shell surface that we interpret as the leached remains of the carbonate fibrils that compose inoceramid shells. If we are correct in this assertion, then the implication is that *Spyridoceramus* ranged considerably higher in the Maastrichtian than other inoceramids (see MacLeod & Ward 1990).

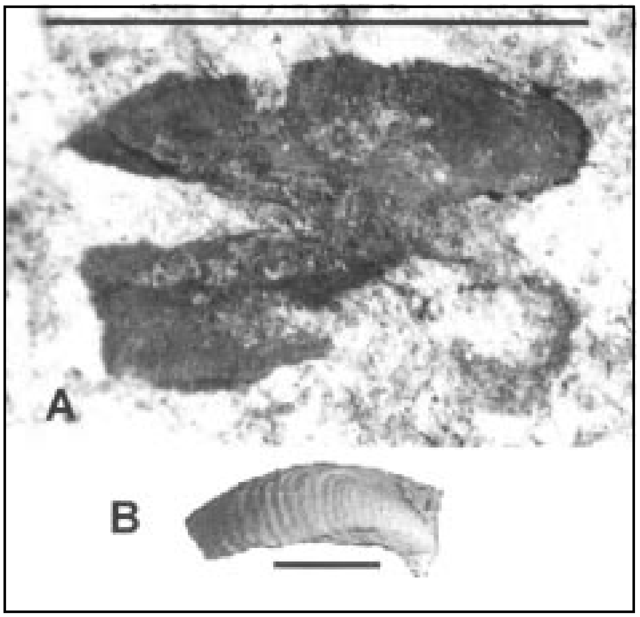


FIGURE 7: *Spyridoceramus (=Tenuipteria) tegulatus*. A: BADL-20468; poorly preserved, partial specimen of a possible S. *tegulatus* collected 10 cm below base of DZ at WATH. B: small "eared" form of juvenile *S. tegulatus*. From Plate 9, Figure 14, of Speden (1970). Scale bars in A and B = 0.5 cm.

Cephalopods

Cephalopods are rare but important components of the Badlands K/T fauna. Two groups of cephalopods are present: scaphitid ammonites and belemnites. Also important is what cephalopods are not present – baculitid ammonites. The absence of baculites from the K/T interval in the Badlands is consistent with the view of Cobban & Kennedy (1992) that these straight-shelled heteromorphs drop out of the record well below the end of the Cretaceous.

Scaphites

Scaphitid ammonites are present in small numbers in the Badlands K/T interval. They occur as rare, isolated fragments usually of the shell flank (Figure 8C, E); and as more complete juvenile shells (Figure 8D). Complete adult specimens (Figure 8A) are exceedingly rare. As a consequence, identification is difficult. Only two species have been identified so far. Further work may increase this number, but it remains to be seen whether the full complement of Maastrichtian scaphite species described by Landman & Waage (1993) from the Fox Hills type area also occurs in the Badlands.

Discoscaphites gulosus (Morton, 1834): The best preserved scaphite yet collected from these beds is the badly crushed, but nearly complete shell shown in Figure 8. The specimen has the adult hook and sutural morphology characteristic of scaphitids (Figure 8B). It is widely umbilicate, and strongly ribbed, with a row of prominent clavate tubercles along the ventrolateral margin of the shell, and a row of large tubercles on the umbilical shoulder. The shell flank also shows at least one row of tubercles. Based on the species definitions given in Landman & Waage (1993), these features, together with the relatively small size of the adult form, suggest that this specimen is a microconch of *Discoscaphites gulosus*. The specimen shown in Figure 8C, although only a small shell fragment, shows two rows of prominent tubercles with each tubercle pair centered on a rib. Ornament of this type is also typically seen in *D. gulosus*.

Jeletzkytes nebrascensis (Owen, 1852): The shell fragment shown in Figure 8E represents a part of the flank of a scaphite shell. Judging from the curvature of the specimen, the fragment extends from about the umbilical shoulder to the ventral shoulder (top to bottom in Figure 8E). The fragment has closely spaced, slightly sinuous and prorsiradiate ribs (about 8 ribs/cm counting along the shell spiral). This suggests that the fragment is from the body chamber of an adult shell. If this is true, then the size of the fragment would indicate that the entire shell probably had a diameter of about 8 to 10 cm. The ribs are of moderate height with most ribs extending from the umbilical to ventral shoulder. Intercalated among the long primary ribs, are several shorter secondary ribs. In addition, small circular tubercles (indicated by white arrows in Figure 8E) are located at intervals along the length of many of the ribs. Part of one large clavate tubercle, can be seen at the ventral shoulder just to the right of the scale bar in Figure 8E. Although it is difficult to determine for certain in so small a fragment, there is some indication that the tubercles are arranged in rows. These features of ribbing and tuberculation, when referenced to species diagnoses given by Landman & Waage (1993) for Fox Hills scaphites, indicate that the specimen is from the shell of *Jeletzkytes nebrascensis*. The estimated diameter of 8 to 10 cm, together with the tuberculation, indicate it is from a small macroconch of this species. Presumably, the original shell resembled YPM23145, a specimen held at Yale Peabody Museum, and illustrated by Landman & Waage (1993, Fig. 123A-D).

J. nebrascensis is among the most common scaphites of the Timber Lake Member in the Fox Hills type area and in adjacent parts of North Dakota (Landman & Waage 1993). That it occurs in the Badlands K/T boundary interval, even

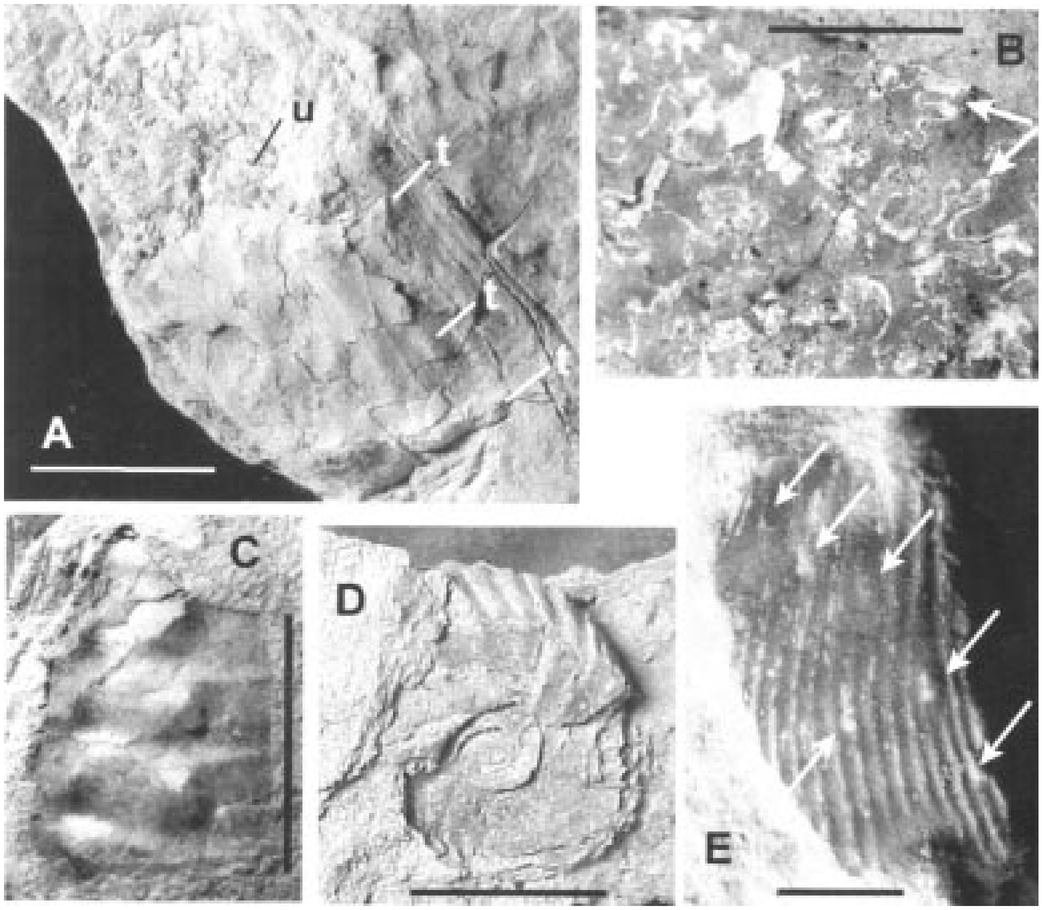


FIGURE 8. Scaphitid ammonites from the Badlands K/T boundary interval. A: adult microconch of *Discoscaphites gulosus* (AMNH-FI-46861) collected within the DZ at Creighton. u – umbilicus; t – tubercle rows (only last tubercle in each row is indicated). Scale bar = 2 cm. (from Figure 2F of Terry et al., 2001). B: enlargement of phragmocone of AMNH-FI-46861 showing partly exposed suture lines of typically scaphitid form. Scale bar = 0.3 cm. C: shell fragment (BC-CR016-00), showing two rows of large tubercles, with pairs of adjacent tubercles positioned on the same rib. Specimen collected 20 cm below DZ at Creighton. Scale bar = 0.5 cm. D: heavily ribbed juvenile scaphite (AMNH-FI-46860) collected 10 cm below the top of the DZ at Creighton. Scale bar = 1 cm. (from Fig 2G of Terry et al. 2001). E: fragment of shell flank of *Jeletzkytes nebrascensis;* (BADL-20479), collected 30 cm below DZ at Dillon Pass. Arrows point to small isolated tubercles characteristic of the species. Scale bar = 0.7 cm.

as a rarity, indicates that its stratigraphic range extends considerably higher than previously documented. *J. nebrascensis* is also an index species for the *J. nebrascensis* ammonite range zone. Thus, the upper boundary for this late Maastrichtian biostratigraphic zone, should be extended upwards to the K/T boundary.

Belemnites

We have collected belemnite specimens in the beds below the DZ at the Wilderness Trailhead locality. None occur higher than about 1 m below the base of the DZ. All appear to be *Belmnitella americana* Morton 1834, the common Western Interior species. The specimens are of the solid, tapering part of the rostrum, and show the radial carbonate prisms characteristic of this structure.

VERTEBRATE FOSSILS

Vertebrate remains are uncommon constitutents of the four Badlands K/T localities discussed here. Osteichthean scales (Figure 9) have been found above, below, and within the DZ at Creighton and they have been found below the DZ at Wilderness Access Trailhead. Chondrichthian remains are also present. A few teeth of lamniform sharks have been recovered from within and above the DZ at Creighton (Figure10A). None of the teeth retain roots, so that it is not yet possible be more precise in their identification. In addition, we have recovered the partial skeleton from Sage Creek Basin of what we interpret as some type of small chondrichthian. This specimen was found as float in the stream bed of the Middle Fork of Sage Creek at the site noted in Figure 2, and discussed above. It undoubtedly weathered out of the adjacent cutbank which exposes late Cretaceous and lower Tertiary rocks. The specimen is preserved in a lenticular concretion of Fox Hills color and character, but the original relation of the specimen to the DZ can not be ascertained. Since the Fox Hills is about 8 m thick at this site, the specimen originally could not have been more than a few meters above or below the DZ, if not originally preserved within it.

As seen in Figure 10B, only a portion of the vertebral column and pectoral girdle, and one of the pectoral fins is preserved. Head and tail are missing. Skeletal elements are

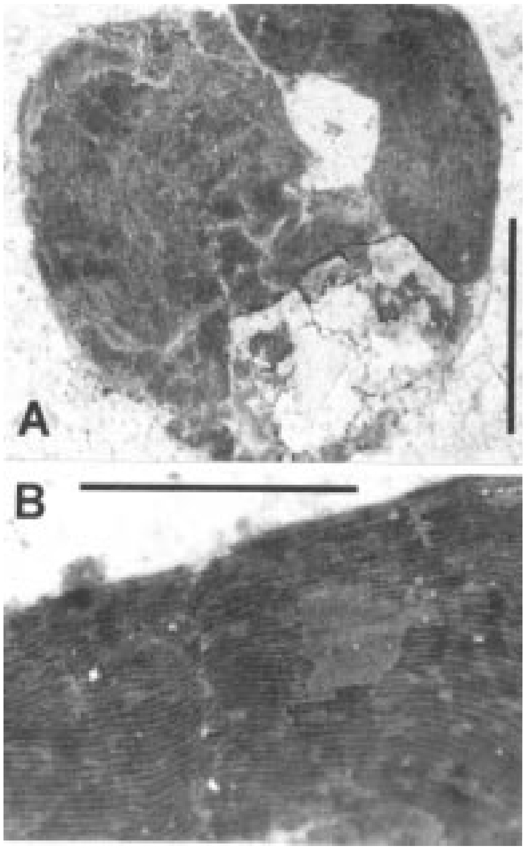


FIGURE 9. Osteichthian fossils in K/T boundary interval. A: osteichthian scale (BADL-20529) collected 40 cm below base of DZ at WATH. Scale bar = 0.5 cm. B: enlargement of A showing crenulated surface ornament of scale. Scale bar = 0.25 cm.

dark or amber colored and appear translucent in strong light. We consider the specimen to be a chondrichthian on the basis of several characters: 1) the vertebrae are simple with a central passage for the notochord that is large relative to the size of the vertebrae; and 2) there is no indication of neural arches, or other osteichthian vertebral structures. We are uncertain as to what kind of a chondrichthian this is, but the elongate body would probably rule out batoids. Our current view is that it is a small, neoselachian shark, but further anatomic analysis is required to fully identify this animal.

TRACE FOSSILS

Bioturbation is a common feature of the sandier beds in all of the Badlands K/T sections discussed here. Trace fossils are also numerous at Wilderness Access Trailhead and Creighton. For the most part, trace fossils found at these two localities belong to the same ichnogenera common in Cretaceous rocks elsewhere in the Western Interior. Op*hiomorpha, Climacodichnus* and *Diplocraterion*-like burrows are particularly prominent in sheet sands at these sites. This is especially true at WATH, where the distorted sandy beds within the DZ and the sand sheet marking the top of the DZ show profuse *Climacodichnus* bioturbation.

In addition to these trace fossils, the WATH section preserves many examples of the feather-like ichnofossil illustrated in Figure 11. These structures occur below and within the DZ, but become more numerous, and better developed, above the DZ, as the section becomes sandier (Figure 5). Superficially, they resemble the crawling traces made by isopod crustaceans in having an elevated central axis, and scour marks arranged in en echelon fashion along the central axis and aligned at acute angles to it (Figure 11C). However, the Badlands ichnofossils differ from isopod trackways in being relatively short, straight structures, rather than the elongate, curved, and often sinuous, trails made by these scavenging epifaunal crustaceans. In addition, isopod trails do not commonly show the elevated periphery present in the better preserved Badlands specimens (Figure 11B).

Although isopods cannot be ruled out as the makers of the Badlands "feather" trails, the identity of the Badlands track maker may lie in another group of benthic crustaceans – anomuran crabs. Figure 12D shows *Emerita*, a burrowing anomuran crab of the New Jersey coastline, known to local saltwater anglers as "mole crab". *Emerita* inhabits the shifting sand of ocean facing beaches, where in the summer it is commonly seen near high tide lines frantically digging back into the sand when exhumed by waves. Figures11E and 11F, show a trackway made by a burrowing *Emerita*. As the animal begins to descend into the sand, it plows up a ridge of sand around its body and the rowing action of its appendages, which push the animal into the sand, produce en echelon sand ridges aligned along the axis of the trackway. Because *Emerita* descends into the substrate within one or two body lengths, its trackway on the sand surface is never more than a few centimeters at most. The result is a structure very much like that of the feather-like Badlands ichnofossils.

In addition, feather trails are most abundant in the upper, sandy part of the WATH exposure, and are invariably associated in these upper sand beds with small circular pits (Fig 11A). These pits taper downwards into the underlying sediment, and are often surrounded by a small raised rim of mounded sand grains. Although they could be incipient cone-in-cone structures, the pits do not show any sign of the chevron laminae characteristic of these sediment dewatering structures. However, they do resemble very closely, particularly with respect to the mounded sand rims, degassation pits that develop in the swath zone of modern beaches, as air trapped interstitially by wave surge migrates upwards and then explosively escapes at the beach surface. The association of the Badlands trails with such structures suggests that the Badlands trackmaker inhabited shifting beach or tidal channel sands as does modern *Emerita*. This strengthens the interpretation of these trails the burrows of this burrowing decapod crustacean.

PALEOECOLOGY

The four K/T boundary localities discussed here preserve invertebrate, vertebrate, and plant remains. Study of this material indicates that Badlands fossils belong to species well known in upper Cretaceous rocks of the Western Interior. But the broad diversity of taxa characterizing the late Cretaceous Western Interior marine fauna does not oc-

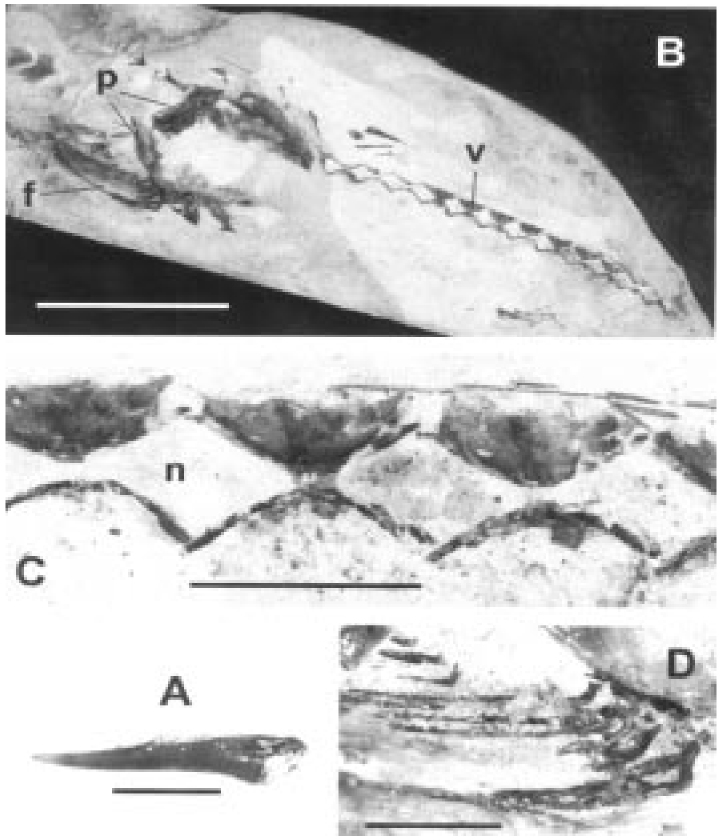


FIGURE 10. K/T boundary interval chondrichthians. A: lamniform shark tooth from within the DZ at Creighton. Scale bar = 0.5 cm. B. Partial chondrichthian skeleton (BADL-20530) from Sage Creek Basin. v – vertebral column; p – pectoral girdle; f – pectoral fin. Scale bar = 3 cm. C: enlargement of vertebral column showing three vertebrae. n – notochord. Scale bar = 0.4 cm. D: proximal region of pectoral fin. Scale bar = 0.5 cm.

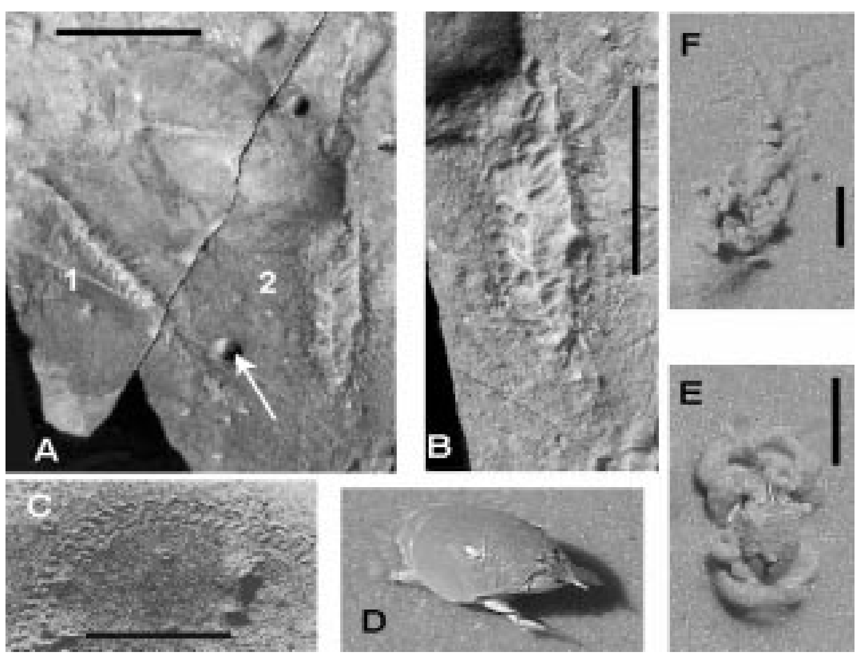


FIGURE 11. K/T interval trace fossils and probable modern analogs. Scale bar = 3 cm in A, B, C, E, F. A, B: feather-like trackways (BADL-20500), collected about 3 m above the DZ at WATH. A: two trackways (1 and 2) on bedding surface of fine grained sandstone. White arrow – degassing bubble crater. B: enlargement of trackway 2 in A. C: trackway of modern nearshore isopod *Oniscus*. (from Fig 127.5 of Hantzschel, 1962). D, E, F: burrowing crab (*Emerita*) and trackways from swath zone of ocean-facing beach at Island Beach State Park, NJ. C: *Emerita,* head at right; tail at left. Total body length – 3 cm. D: animal begins to burrow: E: animal descends below sand surface.

cur in the Badlands K/T interval. Certainly, the species-rich concretionary horizons of the Fox Hills type area described by Waage (1968), Speden (1970) and Landman & Waage (1993) are absent in the Badlands. Instead, one finds at most a few species at a given site, although sometimes in significant numbers. *N. cancellata*, and the feather-trail trackmaker are examples.

To some extent this diminished diversity might reflect destruction of Badlands fossils due to later pedogenic alteration. But this is an unsatisfying explanation because the Creighton section was not affected by paleosol development, and it has a restricted taxonomic diversity little different from the Badlands sites. Moreover, species comprising the fossil-rich sites in the Fox Hills type area, but not occurring at the Badlands sites, have shells that are no more susceptible to geochemical degradation than those species that do occur in the Badlands area. If a wide array of type area species inhabited the Badlands area during the K/T transition, most of these species should still be there, perhaps altered and leached, and reduced in population size, but still present. Thus, we suggest that there is a real ecologic signal coming through the geochemical filter of Interior Zone pedogenesis that reflects original distribution and abundance. This signal indicates that the K/T boundary interval was a time of highly restricted diversity in the Western Interior fauna – at least as we know it from the Badlands. Furthermore, this low diversity is inherently related to conditions within the Seaway. It has nothing to do with the Chicxulub impact because the study localities are faunally impoverished below the impact horizon at the top of the DZ.

Among species preserved in the study area, there are broad differences in numerical abundance between the collecting localities, which are apparent even though we have not yet quantified them. The feather-trail trackmaker is fairly common at Wilderness Access Trailhead, but not found elsewhere, for example. In contrast, nuculids are more abundant at WATH than they are at Dillon Pass, while for scaphites, the situation is reversed. The Grassy Tables Overlook site has no body fossils at all.

To some extent these abundance patterns are undoubtedly the product of later Interior Zone alteration, which varies in intensity across the study area. Thus one would expect carbonate shells to be less abundant in the heavily altered Badlands sites than at Creighton - which they are. But such an explanation does not hold for the feather-trail track maker. Nor can it explain faunal differences among Badlands National Park sites, where the geochemical signature is of roughly equivalent strength. Again, an original ecologic signal is coming through, a signal pointing to local differences in environment and in the distribution patterns of the animals inhabiting the region during K/T transition.

Some understanding of these matters can be gained by reflecting on the paleogeography of the Badlands area during the K/T interval. The core of the issue is the Sage Creek Arch, an anticlinal structure extending roughly NW/SE through the north unit of Badlands National Park. The Badlands K/T sites sit on the southern flank of this structure, near its crest, while Creighton lies to the north. It is evident from the occurrence of intra-formational unconformities and erosive hiatuses within the Fox Hills Formation and the Pierre Shale, as well as from the thinning of the Cretaceous beds over the arch, that the structure was active during the K/T transition (Stoffer, 1998; Stoffer et al., 1998; Stoffer et al., 2001; Terry et al., in review). At times, the crest of the arch was raised above the surface of the Seaway. The discovery of root traces at the top of the Dillon Pass DZ (Terry et al., in review) indicates that the crest was at least partly exposed at the end of the Cretaceous.

Thus, we envision the Badlands area at the K/T boundary to have been a low-lying, sandy peninsula or a series of low sandy islets surrounded by intervening sandy lagoons and tidal channels. The whole structure extended southeastward into the deeper waters of the Western Interior Seaway just offshore. Because the end-K Seaway was smaller, and presumably more restricted oceanographically, than earlier in the Cretaceous, it may have been more inhospitable to stenohaline and stenothermal marine animals, and perhaps less stable environmentally. If so, this would have had an important effect in reducing species diversity at the end of the Cretaceous. The outcrops from which we now collect our K/T fossils were sites of sediment accumulation in the shallow, ephemeral waterways of the crest. Such environments today are often associated with an impoverished macrofauna, in which the few successful forms exist in great numbers. Thus, the prime hallmark of the Badlands during the K/T interval, the impoverishment of its fauna, may have derived from a combination of regional oceanographic factors coupled with local high stress environments. Superimposed on all this in the DZ and the beds immediately above, is the environmental fall-out of the Chicxulub impact.

In the end, how much of this scenario proves to be correct depends very heavily on further research. But the idea that the end of the Cretaceous was an inhospitable time for the biota of the Western Interior seems evident.

THE BADLANDS K/T INTERVAL AND THE END-K MASS EXTINCTION

When Alvarez et al. (1980) suggested that bolide impact was the cause of the terminal Cretaceous mass extinction, they set off a vociferous debate on this subject that continues still. In this debate, attention has centered on dinosaurs and ammonites, the two groups of macroscopic animals whose final extinctions are linked most prominently to the end of the Cretaceous. Much interest has focused on exactly when these lineages terminate relative to the K/T impact horizon. For ammonites this is not exactly clear (Ward 1990), although in most cases, as for example the K/T boundary sections in northern Spain (Ward et al., 1986), ammonites appear to drop out of the record well below the K/T boundary.

The Badlands DZ represents soft sediment deformation due to shock waves emanating from the Chicxulub impact (Stoffer et al. 2001; Terry et al., in review). Thus, in the Badlands the K/T boundary is defined as the horizon separating the top of the DZ from the overlying undisturbed beds (the first one of which at Dillon Pass contains impact ejecta). At Creighton, scaphitid ammonites are preserved within the upper 10 cm of the DZ – within 10 cm of the K/T boundary. Stratigraphic distortion of DZ beds not withstanding, this makes the Badlands scaphites among the youngest ammonites ever reported. But, does this mean that these scaphites survived up to the K/T boundary and that they were indeed victims of the Chicxulub impact? It is too early to say. The distortion of DZ beds; the paucity of scaphites within the DZ; and the ever-present problem of the Signor-Lipps effect (Signor and Lipps, 1982) make a firm conclusion on the exact stratigraphic position of the "last" Badlands scaphites premature. Moreover, the data, as they now exist, also support the view that the Badlands scaphites succumbed slightly before the end of the Cretaceous. If this were the case, then factors other than impact were decisive. In this alternative scenario, paleoenvironmental change deriving from the latest Maastrichtian sea level low stand (Haq et al., 1987), which some advocate to have occurred about two hundred thousand years prior to the K/T transition (Stinnesbeck & Keller, 1996), offers a plausible alternative explanation for the extinction of the Badlands scaphites. Further collection work with a focus on microfossil, as well as scaphite, biostratigraphy should prove useful in resolving this issue.

ACKNOWLEDGMENTS

We thank A. Chamberlain, L. Factor, P. Jannett, P. Messina, J. Mundt, and D. Patrick for help in the field. R. Benton, Paleontologist at Badlands National Park, provided research permits and advice on field logistics. N. Landman assisted in identification of the scaphitids; and T. White and C. MacClintock assisted in our study of Fox Hills specimens held at the Yale Peabody Museum. This research was supported by grants to JAC from the PSC-CUNY Research Award Program of the City University of New York, and NSF (STI-9602595); a grant to JAC and PWS from the EDMAP program of the USGS; and a grant to DOT from the College of Science and Technology at Temple University.

REFERENCES

Alvarez, L.W., W. Alvarez, F. Asaro, and H.V. Michel, 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction. *Science*, 208**:**1095-1108.

Cobban, W.A., 1993. Diversity and distribution of Late Cretaceous ammonites, Western Interior, United States: in Caldwell, W.G.E., and Kauffman, E.G., eds., Evolution of the Western Interior Basin. *Geological Association of Canada, Special Paper,* 39:435-451.

____, and W.J. Kennedy, 1992. The last Western Interior *Baculites* from the Fox Hills Formation of South Dakota. *Journal of Paleontology*, 66**:**690-692.

Conrad, T.A., 1858. Observations on a group of fossil shells found in Tippah county, Miss., with descriptions of fifty-six new species. *Academy of Natural Sciences of Philadelphia Journal*, ser. 2: 3**:**327-336.

Gill, J.R., and W.A. Cobban, 1966. The Red Bird section of the upper Cretaceous Pierre Shale in Wyoming. *US Geological Survey, Professional Paper*, 393-A:1-73.

Hantzschel, W. 1962. Trace fossils and Problematica. in R.C. Moore, ed*., Treatise on Invertebrate Paleontology*, Vol. W. Miscellanea, Univ. Kansas Press, Lawrence, KS, pg. 177-245.

Haq, B.U., J. Hardenbohl, and P. Vail, 1987. Chronology of fluctuating sea level since the Triassic. *Science*, 235:1156-1166.

Izett, G.A., W.A. Cobban, G.B. Dalrymple, and J.D. Obradovich, 1998. $^{40}Ar/^{39}Ar$ age of the Manson impact structure, Iowa, and correlative impact ejecta in the Crow Creek Member of the Pierre Shale (Upper Cretaceous), South Dakota and Nebraska. *Geological Society of America Bulletin*, 110:361-376.

Kauffmann, E.G., 1977. Illustrated guide to biostratigraphically important Cretaceous macrofossils, Western Interior Basin: U.S.A. *Mountain Geology*, 14:225-274.

____, B.B. Sageman, J.I. Kirkland, W.P. Elder, P.J. Harries, and T. Villamil, 1993. Molluscan biostratigraphy of the Cretaceous Western Interior Basin, North America: in Caldwell, W.G.E., and Kauffman, E.G., eds., Evolution of the Western Interior Basin. *Geological Association of Canada, Special Paper***,** 39: 397-434.

Kennedy, W.J., N.H. Landman, W.K. Christiansen, W.A. Cobban, and J.M. Hancock, 1998. Marine connections in North America during the late Maastrichtian: paleogeographic and paleobiogeographic significance of *Jeletzkytes nebrascensis* zone cephalopod fauna from the Elk Butte Member of the Pierre Shale, SE South Dakota and NE Nebraska, *Cretaceous Research*, 19: 745-775.

Landman, N.H., and K.M. Waage, 1993. Scaphitid ammonites of the upper Cretaceous (Maastrichtian) Fox Hills Formation in South Dakota and Wyoming. *Bulletin of the American Museum of Natural History,* 215:1-257.

MacLeod, K.G., and P.D. Ward, 1990. Extinction pattern of *Inoceramus* (Bivalvia) based on shell fragment biostratigraphy: in Sharpton, V.S., and Ward, P.D., eds., Global Catastrophes in Earth History*, Geological Society of America Special Paper* 247: 509-518.

Meek, F.B., and F.V. Hayden, 1856. Descriptions of twenty eight new species of *Acephela* and one gasteropod, from the Cretaceous formations of Nebraska Territory. *Academy of Natural Sciences of Philadelphia Proceedings*, 8:81-87.

Morton, S.G., 1834. Synopsis of organic remains of the Cretaceous Group of the United States. W.P. Gibbons, Philadelphia.

Obradovich, J.D., 1993. A Cretaceous time scale: in Caldwell, W.G.E., and Kauffman, E.G., eds., Evolution of the Western Interior Basin. *Geological Association of Canada, Special Paper,* 39:379-396.

Owen, D.D., 1852. Description of new and imperfectly known genera and species of organic remains, collected during the geological surveys of Wisconsin, Iowa, and Minnesota. in Report of a geological survey of Wisconsin, Iowa, and Minnesota; and incidentally of a portion of Nebraska Territory. Lippincott, Philadelphia, p.573-587.

PETTYJOHN, W.A., 1967. New members of upper Cretaceous Fox Hills Formation in South Dakota, representing delta deposits. *American Association of Petroleum Geologists Bulletin,* 51:1361-1367.

RETALLACK, G.J., 1983. Late Eocene and Oligocene paleosols from Badlands National Park, South Dakota. *Geological Society of America, Special Paper,* 193**:**1-82.

SIGNOR, P. W. III, and J.H. LIPPS, 1982. Sampling bias, gradual extinction patterns and catastrophes in the fossil record: in Silver, L.T. and Schultz, P.H., eds., Geological implications of impacts of large asteroids and comets on the earth: *Geological Society of America, Special Paper,* 190**:**291-296.

SMIT, J., T.B. ROEP, W. ALVAREZ, A. MONTANARI, P. CLAEYS, J.M. GRAJALES-NISHIMURA, J. BERMUDEZ, 1996. Coarse-grained, clastic sandstone complex at the K/T boundary around the Gulf of Mexico: deposition by tsunami waves induced by the Chixculub impact? In in Ryder, G., Fastovsky, D., and Gartner, S., eds., The Cretaceous-Tertiary Event and Other Catastrophes in Earth History, *Geological Society of America, Special Paper,* 307:151-182.

SPEDEN, I.G., 1970. The type Fox Hills Formation, Cretaceous (Maestrichtian), South Dakota: Part 2. Systematics of the Bivalvia. *Peabody Museum of Natural History Bulletin*, 33:1-222.

STINNESBECK, W., and KELLER, G., 1996. K/T boundary coarse-grained siliciclastic deposits in northeastern Mexico and northeastern Brazil: evidence of mega-tsunamis or sea level changes?: in Ryder, G., Fastovsky, D., and Gartner, S., eds., The Cretaceous-Tertiary Event and Other Catastrophes in Earth History, *Geological Society of America, Special Paper,* 307:197-209.

STOFFER, P.W., 1998. Stratigraphy of the Pierre Shale and Fox Hills Formation (Late Cretaceous) in the Badlands National Park area, South Dakota: Implications for eustacy, tectonism, and marine paleoecology of the Western Interior Seaway. Ph.D. Dissertation, City University of New York, 501 pg.

_____, P. MESSINA, and J.A. CHAMBERLAIN, Jr., 1997. Buried slumps in the upper Pierre Shale/Fox Hills transition interval in Badlands National Park*, Geological Society of America Abstracts with Programs Annu. Meetings*, 29:A274.

_____, _____, and _____, 1998. Cretaceous stratigraphy of Badlands National Park: implications for eustacy, tectonism, and marine paleoecology of the Western Interior Seaway. *Dakoterra* , 5:55-62.

_____, _____, _____, and Terry, D.O., Jr., 2001. The Cretaceous-Tertiary boundary interval in Badlands, National Park, South Dakota. *U.S. Geological Survey, Open File Report 01-56,* 1-49.

TERRY, D.O., JR., and J.E. EVANS, 1994. Pedogenesis and Paleoclimatic Implications of the Chamberlain Pass Formation, Basal White River Group, Badlands of South Dakota. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 110:197-215.

____, J.A. CHAMBERLAIN, JR., P.W. STOFFER, P. MESSINA, and P. JANNETT, (in press). A marine K/T boundary in southwestern South Dakota. *Geology.*

WAAGE, K.M., 1968. The type Fox Hills Formation, Cretaceous (Maestrichtian), South Dakota, Part 1, stratigraphy and paleoenvironments. *Peabody Museum of Natural History Bulletin*, 27:1-175.

WARD, P.D., J. WIEDMANN, and J. MOUNT, 1986. Maastrichtian molluscan biostratigraphy and extinction patterns in a Cretaceous/Tertiary boundary section exposed at Zumaya, Spain. *Geology*, 14:899-903.

____, 1990. A review of Maastrichtian ammonite ranges: in Sharpton, V.S., and Ward, P.D., eds., Global Catastrophes in Earth History. *Geological Society of America, Special Paper,* 247:519-530.

THE FIRST RECORD OF BIRD EGGS FROM THE EARLY OLIGOCENE (ORELLAN) OF NORTH AMERICA

ROBERT M. CHANDLER AND WILLIAM P. WALL
Dept. of Biology, Georgia College & State University, Milledgeville, GA 31061

ABSTRACT—Three bird eggs from the Scenic Member of the Brule Formation, Badlands National Park, Shannon County, South Dakota are the first published record of eggs from the early Oligocene (Orellan) of North America. The fossil eggs compare closest to gruiform birds: cranes, rails, limpkins, and their relatives (Aves: Gruiformes) in size, shape, and eggshell porosity. Our understanding of the Paleogene paleo-avifauna is based on fossil skeletons from a limited number of well-known Eocene and fewer Oligocene localities. Eocene and Oligocene gruiform bird species are known; one of which is the earliest record of a limpkin, *Badistornis aramus* Wetmore, from Shannon County, South Dakota. The eggs described herein compare closest to eggs of the living Limpkin, *Aramus guarauna*.

Beginning in 1987 field crews from Georgia College & State University (GC&SU) have intensively surface-collected fossiliferous beds in the Brule Formation in the South Unit of Badlands National Park. While mammal fossils comprise the majority of specimens contained in the Badlands strata, there is a significant herpetofauna as well (Maddox & Wall, 1998; Wall & Maddox, 1998).

Few bird fossils have been found in the Badlands National Park and the surrounding area over the 150 years of paleontological studies there. In general, our understanding of Paleogene birds is from species known from the Eocene of France, North America, and the United Kingdom (Feduccia, 1996:167-171). Therefore, any additional information about Paleogene birds, and especially pertaining to the Paleocene and the Oligocene, is important. This paper provides the first record of bird eggs from the early Oligocene (Orellan) of North America.

SYSTEMATIC PALEONTOLOGY

[An asterisk (*) indicates genera and species described from the Badlands National Park. The following acronyms are used: Georgia College & State University, Vertebrate Paleontology collections (GCVP); Museum of South Dakota School of Mines & Technology (SDSM)].

Order Gruiformes

(cranes, rails, limpkins, and their relatives)

Family Aramidae

(limpkins)

cf. *Genus *Badistornis*

(extinct limpkin)

cf. **Badistornis aramus* Wetmore 1940

Holotype.- SDSM 3631, left tarsometatarsus missing the hypotarsus, collected in the *Metamynodon* zone river channel sandstone of the Brule beds, Upper White River (Orellan), Shannon Co., South Dakota.

Badistornis aramus Wetmore (1940:30) is the earliest record for a limpkin in North America (Brodkorb, 1967:155). In his "Remarks" section, Wetmore states, "The close general resemblance of the fossil specimen to the metatarsus of the living *Aramus scolopaceus* [=*A. guarauna*] is such as to leave no doubt almost at glance that it is a species of the family Aramidae." The tarsometatarsus of *Badistornis aramus* is slightly longer than that of the Limpkin: holotype = 155mm vs. *A. guarauna* = 113-123mm (n=6, Gilbert, et al., 1981:234). However, osteologically the characteristics of the holotype are that of a limpkin.

New material: Three bird eggs from the Southern Unit of Badlands National Park (Fig. 1 A-C). Two of the specimens (GCVP 3610 and 3682) were found near the southern end of Cedar Butte (GC&SU locality SDS 12). The third egg (GCVP 3958) is from the southern end of Big Corral Draw (GC&SU locality SDS 9; Fig. 3).

Description: GCVP 3610 (Fig. 1A) is in the best state of preservation of the three eggs, with little or no distortion and only slight cracking. Its overall geometry (elongation average, bicone average, asymmetry; as defined by AOU, 1962:13; Preston, 1953:166; Preston, 1968) is elliptical in profile and equal to that of the Aramidae (Preston, 1969:248, Table 1). The porous nature of the eggshell is preserved and compares well with that of Limpkin eggs (Fig. 2).

GCVP 3682 is slightly more distorted by compression than GCVP 3610 with many more cracks (Fig. 1B). Although not as well preserved, the elliptical geometry and the porous nature of the eggshell is still apparent.

GCVP 3958 is in the poorest state of preservation with numerous cracks and flattening. However, the elliptical geometry and porous nature of the eggshell is preserved (Fig. 1C).

All three eggs were x-rayed but no embryos or internal structures were observed.

Measurements: GCVP 3610 = length 58.11mm x width 44.13mm; GCVP 3682 = [54.56]mm x [46.12]mm; GCVP 3958 = [55.46]mm x [39.08]mm; Limpkin (*Aramus guarauna*) 55-64mm x 41-47mm (Walters, 1994:82).

GEOLOGY

Fossiliferous exposures in the gullies where these eggs were collected are Orellan (Scenic member, Brule Formation) in age. All the eggs were collected in float, but based on the stratigraphy of the fossil-bearing horizons a more narrowly defined time interval can be inferred.

GCVP 3610 was collected approximately 15 meters above ground level. Based on the mammal fauna (particularly *Miniochoerus gracilis*) contained in the only fossil-bearing horizon above that level in the gully, the most likely age for this egg is approximately 32.5 million years (early in Chron C12r of Prothero and Whittlesey, 1998). The same gully produced an unusually high frequency of *Leptictis dakotensis* specimens (three skulls and four lower jaws in less than two man hours of collecting). While this taxon has no biostratigraphic value its abundance in this gully may have some paleoecologic significance.

GCVP 3682 was collected in a gully approximately 200 meters from the gully containing GCVP 3610. This egg was collected at ground level just below a narrow fossil-rich horizon (approximately 2 meters thick) in a nodular zone. This locality also produced specimens of *Ischyromys parvidens* therefore the most likely age for this egg is 33 million years (Chron C13n of Prothero and Whittlesey, 1998).

GCVP 3958 was collected in float approximately 10 meters above the *Metamynodon* channel sandstone. The Orellan section in this locality is highly fossiliferous over multiple horizons, therefore this specimen cannot be assigned with confidence to a specific Chron but it is clearly younger than the early Orellan.

Retallack (1983, 1992) recognized four major habitats in Badlands during the Orellan. These are: streamside swales, near stream, open forest, and savanna. Based on the lithology and associated fauna at the bird egg localities these areas were most likely near stream or open forest habitats.

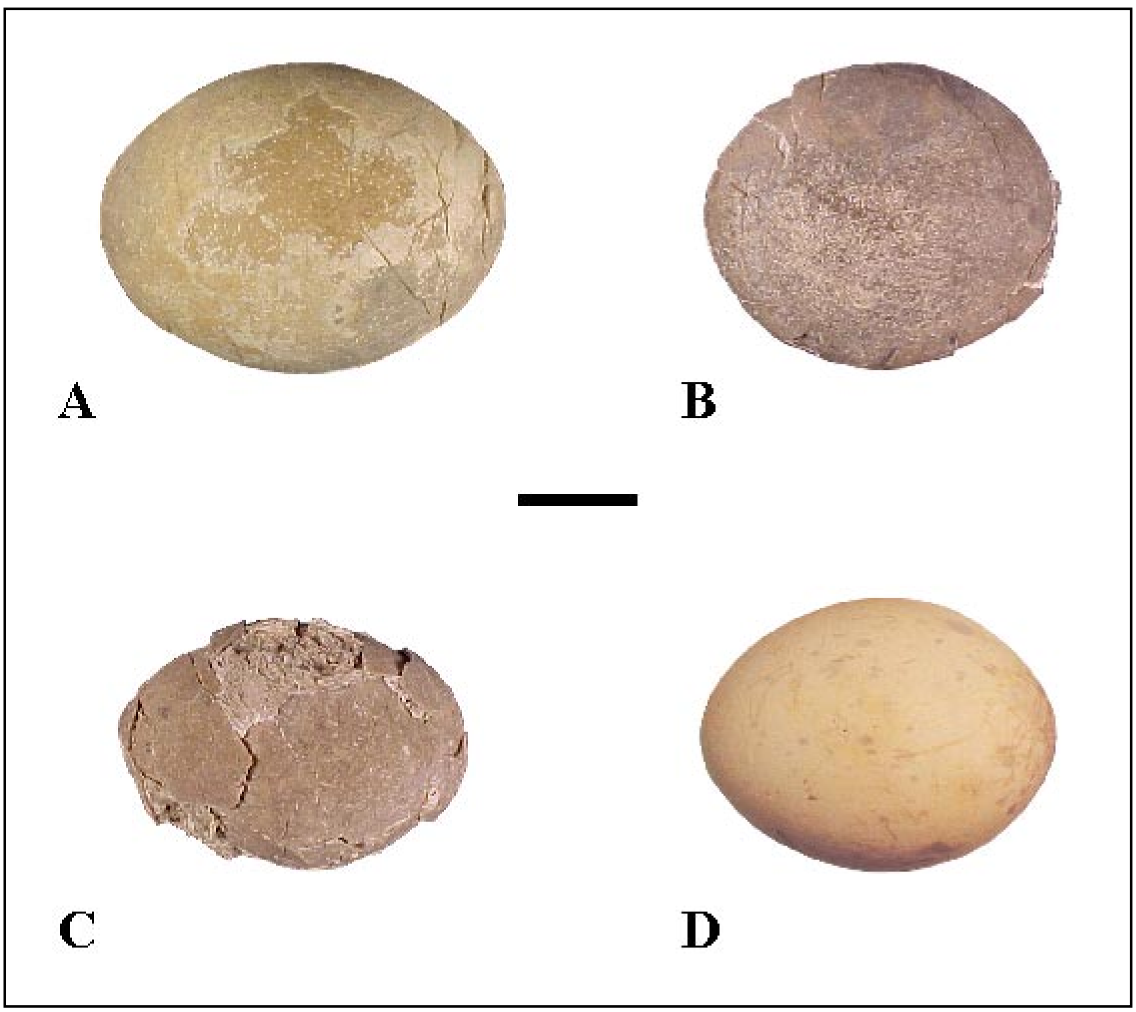


FIGURE 1. A, GCVP 3610; B, GCVP 3682; C, GCVP 3958; and D, egg from a modern Limpkin (*Aramus guarauna*) as illustrated in Walters (1994). Scale bar equals 2 cm.

FIGURE 2. Detailed view of GCVP 3610 showing the porosity pattern characteristic of the eggshells of limpkins.

Prothero (1994) provides a useful overview of paleoclimate and faunal composition during the early Oligocene in North America.

DISCUSSION

In overall geometry (elongation average, bicone average, asymmetry) and eggshell porosity, and texture GCVP 3610 compares closest to the egg of the Limpkin, *Aramus guarauna*. GCVP 3682 and 3958 both compare very closely to GCVP 3610. An extinct limpkin, *Badistornis aramus* Wetmore, has been described from essentially the same locality (using identical stratigraphic, lithologic, and age criteria). Although *B. aramus* did have slightly longer tarsometatarsi than *A. guarauna,* overall the birds would be of very similar body size and weight. It can be surmised that these two closely related species of North American limpkins would have had eggs of similar size and shape. There are other extinct birds represented in the fossil record during the early Oligocene such as a guan and a quail (Galliformes: Cracidae, Phasianidae, respectively), a hawk (Falconiformes: Accipitridae), and an extinct relative of the modern seriema (Bathornithidae), but all of these living birds have eggs of a very different shape and/or size.

There is a published record of an early Miocene possible duck egg from South Dakota (Farrington, 1899). However, the collecting data is simply "region of the Bad Lands" and, therefore, the age is also questionable. O'Harra (1920:143) cites Farrington's report and states that there are other badlands bird eggs in museums, as was also noted by one of our reviewers, but as yet these are unstudied and unpublished specimens and are, therefore, not science.

We agree with the modern bird literature, e.g., Pettingill (1985:296), that modern bird eggs are best identified in the nest with an adult either sitting on the nest or identifying the species before it flushes from the nest, however, the birds that laid the eggs described herein flushed many millions of years ago.

ACKNOWLEDGEMENTS

We thank Dr. Rachel Benton of Badlands National Park for her extensive support of our research efforts and Mr. Vince Santucci for his enthusiasm and support for paleontological research in the National Parks. We would like to thank Ms. Linda D. Chandler and two anonymous reviewers for critically reading the manuscript. Linda Chandler also helped with illustrations. Ms. Elaine Zeiger, Geology Department, Field Museum of Natural History, provided a copy of the Farrington publication. Dr. Sara Toni Hall took x-rays of the bird eggs and discussed the results with RMC. This research was partially funded by faculty research grants from Georgia College & State University.

REFERENCES

AMERICAN ORNITHOLOGISTS' UNION, 1962. Handbook of North American Birds. R.S. Palmer (ed.). Yale University Press, New Haven and London, Vol. 1, 567 pp.

BRODKORB, P., 1967. Catalogue of fossil birds: Part 3 (Ralliformes, Ichthyornithiformes, Charadriiformes). Bulletin of the Florida State Museum, Biological Sciences, 11(3):99-220.

FARRINGTON, O.C., 1899. A fossil egg from South Dakota. Field Columbian Museum, Geological Series, Publication 35, v. 1(5):193-200.

FEDUCCIA, A., 1996. The Origin and Evolution of Birds. Yale University Press, New Haven and London, 420 pp.

GILBERT, B. M., L.D. MARTIN, and H.G. SAVAGE, 1981. Avian Osteology. B. Miles Gilbert, Publisher, 252 pp.

HARRIS, A. G., E. TUTTLE, and S.D. TUTTLE, 1995. Geology of National Parks. Kendall/Hunt Publishing Company, Dubuque, 758 pp.

MADDOX, D. and W.P. WALL, 1998. A systematic review of the fossil lizards and snakes (Squamata) from the White River Group of Badlands National Park. National Park Service Paleontological Research Vol. 3 Technical Report NPS/NRGRD/GRDTR-98/1, pp. 4-7.

O'HARRA, C.C. 1920. The White River Badlands. Bulletin No. 13, Department of Geology, South Dakota School of Mines and Technology, Rapid City, South Dakota. 181pp.

PETTINGILL, O.S., Jr., 1985. Ornithology in laboratory and field. 5th ed. Academic Press, Harcourt Brace Jovanovich, San Diego, 403 pp.

PRESTON, F.W., 1953. The shapes of birds' eggs. The Auk 70(2):160-182.

_____ , 1968. The shapes of birds' eggs: mathematical aspects. The Auk 85(4):454-463.

_____, 1969. Shapes of birds' eggs: extant North American families. The Auk 86(2):246-264.

PROTHERO, D.R., 1994. The Eocene-Oligocene transition. Paradise Lost. Columbia University Press, New York, 283 pp.

_____ and K.E. WHITTLESEY, 1998. Magnetic stratigraphy and biostratigraphy of the Orellan and Whitneyan land mammal "ages" in the White River Group. Pp.39-61 *in:* D.O. Terry, H.E. LaGarry, and R.M. Hunt (eds.), Depo-

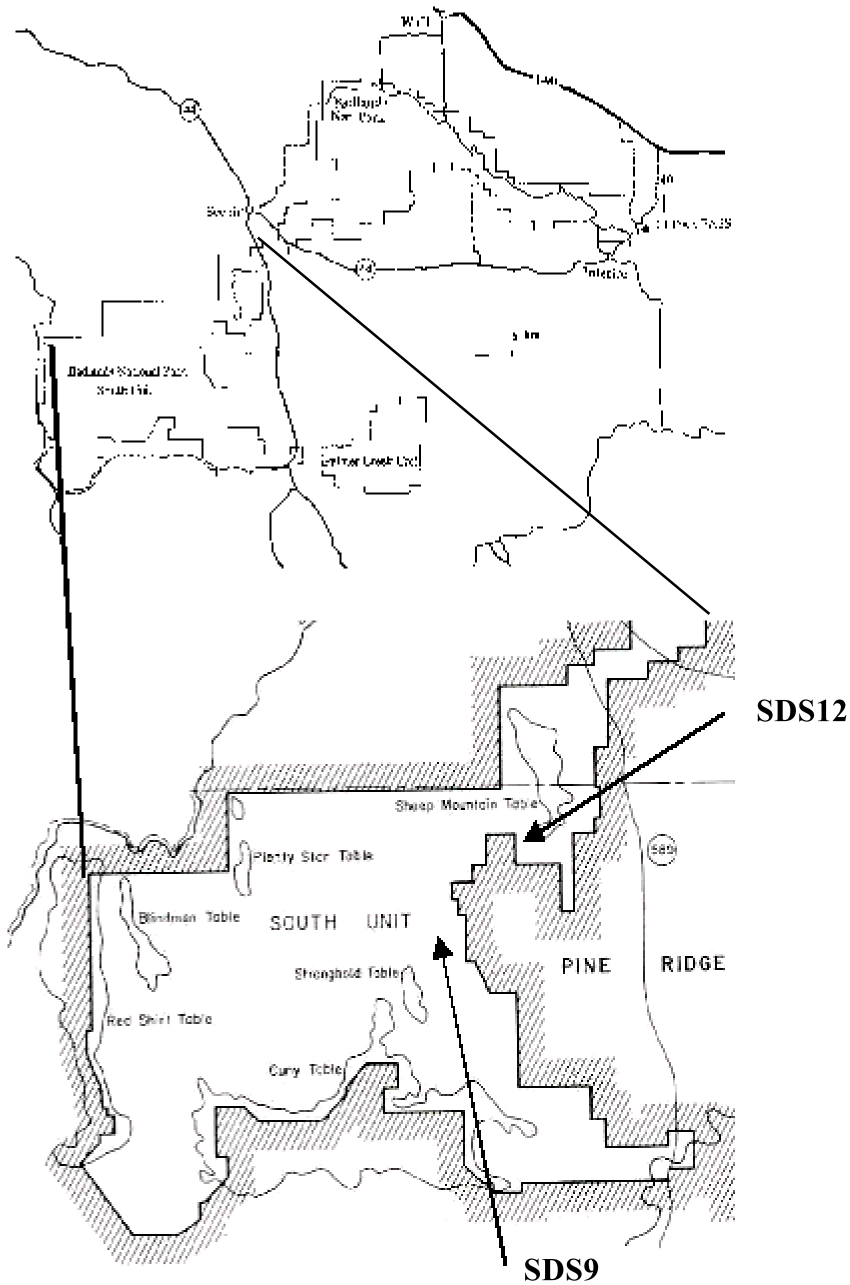


FIGURE 3. Map of Badlands National Park showing general locality information. The enlarged portion of the map is modified from Harris et al., (1995).

sitional Environments, Lithostratigraphy, and Biostratigraphy of the White River and Arikaree Groups (late Eocene to early Miocene, North America). Geo. Soc. Amer. Sp. Paper 325.

RETALLACK, G.J., 1983. A paleopedological approach to the interpretation of terrestrial sedimentary rocks: the mid-Tertiary fossil soils of Badlands National Park, South Dakota. Geological Society of America Bulletin 94:823-840.

______, 1992. Paleosols and changes in climate and vegetation across the Eocene/Oligocene boundary. *in* Eocene/Oligocene Climate and Biotic Evolution. Princeton University Press: New York. pp.382-398.

WALL, W.P. and D. MADDOX, 1998. Reassessment of characteristics determining generic affinity in *Gopherus* and *Stylemys* (Testudinidae) from the White River Group, Badlands National Park. National Park Service Paleontological Research Vol. 3 Technical Report NPS/NRGRD/GRDTR-98/1, pp. 8-12.

WALTERS, M., 1994. Birds' Eggs. Dorling Kindersley, London, New York, Stuttgart, 256 pp.

WETMORE, A., 1940. Fossil bird remains from Tertiary deposits in the United States. Journal of Morphology, 66(1):25-37.

CRETACEOUS ELASMOBRANCHS OF THE GREENHORN FORMATION (MIDDLE CENOMANIAN-MIDDLE TURONIAN), WESTERN SOUTH DAKOTA

DAVID J. CICIMURRI
Bob Campbell Geology Museum, Clemson, SC, 29634

Abstract— Cooperation between the U.S. Forest Service, Bureau of Recreation, and the South Dakota School of Mines and Technology has resulted in the accumulation of a significant collection of elasmobranch fossils from the Greenhorn Formation of western South Dakota. Thirteen taxa were recovered from late Cenomanian rocks of the lower portion of the formation, whereas 14 taxa were collected from early middle Turonian rocks at the very top of the formation. Both of these assemblages are dominated by pelagic taxa. A few of the sharks and rays within the lower and middle portions of the formation are consistently found in rocks representing shallow-water environments, indicating that several regressive episodes occurred during the transgressive phase of the Greenhorn Cyclothem. The elasmobranch assemblages from the Greenhorn Formation of South Dakota are similar (or nearly identical) to those from temporally equivalent rocks of Texas, Kansas, and Arizona. The absence of these taxa in the Atlantic and West Coast regions is due to the lack of appropriate-aged strata in these areas.

INTRODUCTION

The Greenhorn Formation is exposed around the Pre cambrian core of the Black Hills of South Dakota and Wyoming. Despite this fact, the formation has largely been neglected with regard to its paleontological resources. Recently, the South Dakota School of Mines and Technology, in conjunction with the U.S.F.S. and U.S.B.R., has been conducting a systematic study of the formation within South Dakota. Museum personnel have discovered a diverse plesiosaur assemblage in the formation, including the first occurrence of the large pliosaur *Polyptychodon interruptus* in the Western Interior of North America (VonLoh and Bell 1998).

Squamates from the Greenhorn include the enigmatic dolichosaur *Coniasaurus crassidens*, as well as a basal mosasauroid and another poorly understood taxon (Bell 1993; Bell and VonLoh 1998). Most unexpectedly, a pterosaur wing metacarpal was collected from the middle portion of the formation, and a neonatal chelonioid costal was found in the uppermost part of the formation (VonLoh and Bell 1998).

Cobban (1951) noted the presence of teleosts in the base of the formation at Orman Lake, but stated that remains were too fragmentary for a generic identification. Later, Foell (1982) reported the large teleost *Xiphactinus audax*. In addition to this taxon, SDSM has collected *Enchodus*, *Protosphyraena*, *Pachyrhizodus*, and *Micropycnodon*. Prior to this report, elasmobranch distributions within the Greenhorn Formation of South Dakota were virtually unknown. Cobban (1951) reported *Isurus appendiculata* (= *Cretolamna appendiculata*), *Isurus desorii* (= *Cretoxyrhina mantelli*), *Squalicorax falcatus*, and *Ptychodus whipplei*, and Martin et al. (1996) noted the presence of odontaspidids.

ABBREVIATIONS

Institutional - **AMM**, Adams Memorial Museum, Deadwood, SD; **SDSM**, Museum of Geology, South Dakota School of Mines and Technology, Rapid City.

Other - **AR**, Angostura Reservoir, Fall River County, SD; **BFR**, Belle Fourche Reservoir, Butte County, SD; **E**, Edgemont, Fall River County, SD; **OLM**, Orman Lake Limestone Member, Greenhorn Formation; **PCM**, Pool Creek Member, Carlile Shale.

GEOLOGIC SETTING

The Late Cretaceous Greenhorn Formation was deposited in a north-south trending inland seaway between the cordilleran mobile belt to the west and the stable North American craton to the east (Macdonald and Byers 1988). Exposures of the formation are extensive in Colorado, Kansas, Wyoming, Nebraska, South Dakota, and northern New Mexico (Hattin 1975). In the Black Hills region of South Dakota, the Greenhorn Formation is exposed around the Precambrian core of the Black Hills Uplift (Figure 1). This area is also the site of a facies change within the formation from carbonate-rich facies to the south and east, and clay-rich facies to the west (Hattin 1975; Macdonald and Byers 1988). Greenhorn carbonate rocks are thought to have been deposited far from the nearest shorelines in relatively deep, mostly quiet-water environments where pelagic sedimentation prevailed. There is considerable debate as to water depth of the Western Interior Seaway during deposition of the Greenhorn Formation. Using microinvertebrate and geological structure data, Hattin (1975) and Kauffman (1969) suggested that deposition occurred in middle to outer shelf depths (100-200 m maximum) except during regression when the depth was shallower. Based on reconstructed slope measurements

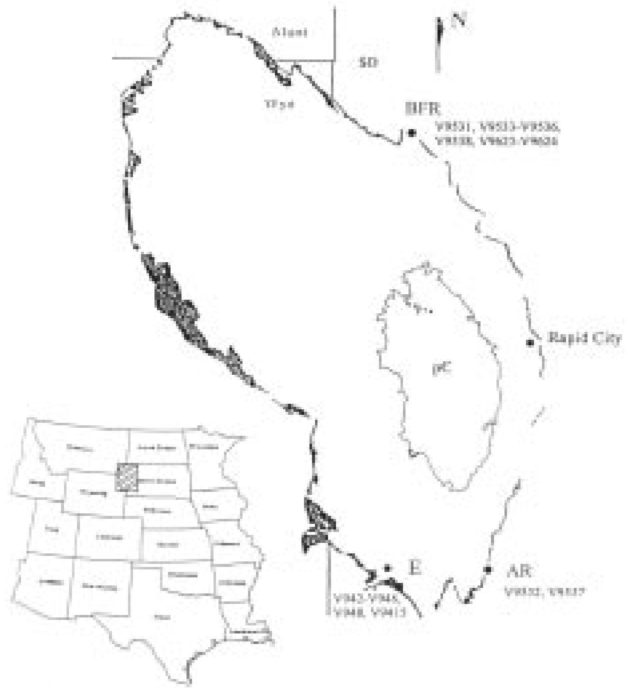


FIGURE 1. Exposures of the Greenhorn Formation around the Black Hills. BFR (Belle Fourche Reservoir), AR (Angostura Reservoir), and Edgemont (E) are the primary localities discussed in the text. SDSM localities for each location are indicated (i.e. V9536 is at BFR). pC = Precambrian core of the Black Hills Uplift.

and microinvertebrates, Eicher (1967) suggested that water depth during maximum transgression was 915 m.

In western South Dakota the Greenhorn consists predominately of marl and calcareous shale, with abundant limestone concretions, thin to moderately thick limestone beds, and bentonites. West of this area the unit grades into non-calcareous shale of the Marias River, Frontier, and Mancos formations (Williamson et al. 1993). There is a lithologic difference in the Greenhorn Formation between the northern and southern limits of the Black Hills, which is probably the result of diachronous deposition within the basin, but could also be due to unconformities. Cobban (1951) described the Greenhorn Formation in the northern Black Hills using four informal lithologic units, but only the basal member was named. This basal unit was named the Orman Lake Member for exposures around Orman Lake (Belle Fourche Reservoir) near Belle Fourche, South Dakota. The formation reaches a maximum thickness of 110 m in Crook County, Wyoming, but in the study area the maximum measured thickness is 63 m (southern Black Hills at Angustora Reservoir). Maximum thickness in the northern Black Hills has not been determined because of a lack of continuous outcrops.

The Greenhorn Formation overlies non-calcareous shale of the Belle Fourche Shale, and underlies black non-calcareous shale of the PCM. In the southern Black Hills, the Belle Fourche and Greenhorn are separated by a thick bentonite that Cobban (1951) has called the "X" bentonite (Figure 2). This bentonite appears to be missing in the northern Black Hills, where basal beds of the Orman Lake Member unconformably overlie the Belle Fourche Shale (Figure 3). The Cenomanian-Turonian boundary is located near the middle of the Greenhorn Formation, not far above the "B" bentonite of Elder (1986). This distinctive bentonite is exposed both in the northern and southern portions of the Black Hills of South Dakota (Figure 4). There may be an unconformity at the top of the formation in the northern Black Hills, indicated by vertebrate lag beds and an abrupt change from light colored limestone and marl to dark non-calcareous shale (Figure 5). In the southern Black Hills, the top of the formation is placed at the contact between a gradational interval of 18 m of calcarenites and black non-calcareous shale of the PCM.

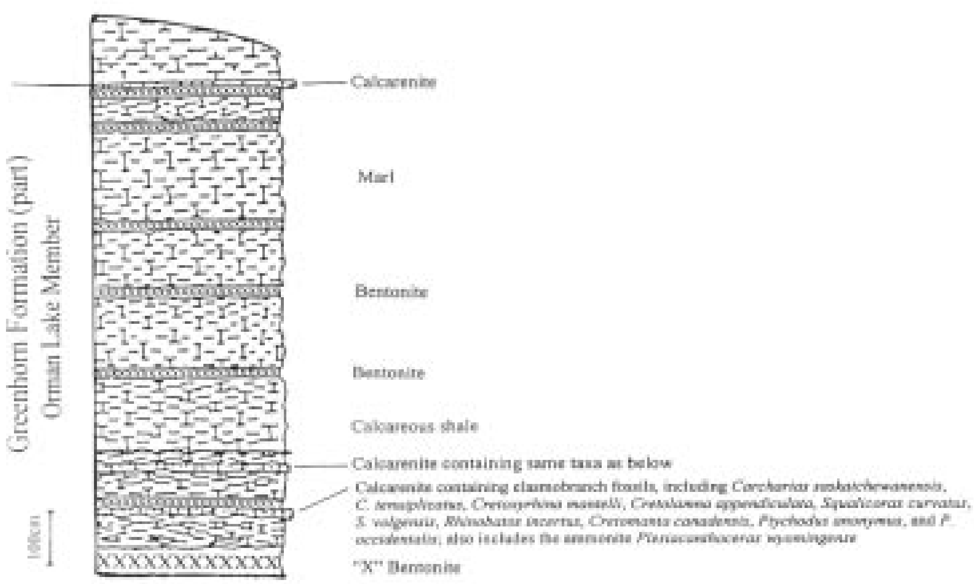


FIGURE 2. Stratigraphic section of the entire OLM, Greenhorn Formation, as exposed at the southern portion of AR, Fall River Co., SD. The contact with the Belle Fourche Shale is just below the base of the "X" bentonite.

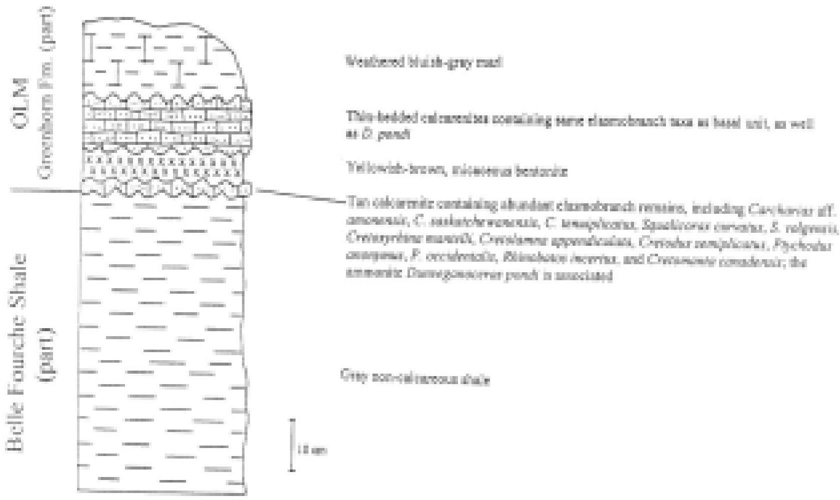


FIGURE 3. Stratigraphic section of the Belle Fourche Shale/Greenhorn Formation contact as exposed at the southeast end of BFR, Butte Co., SD. OLM = Orman Lake Member.

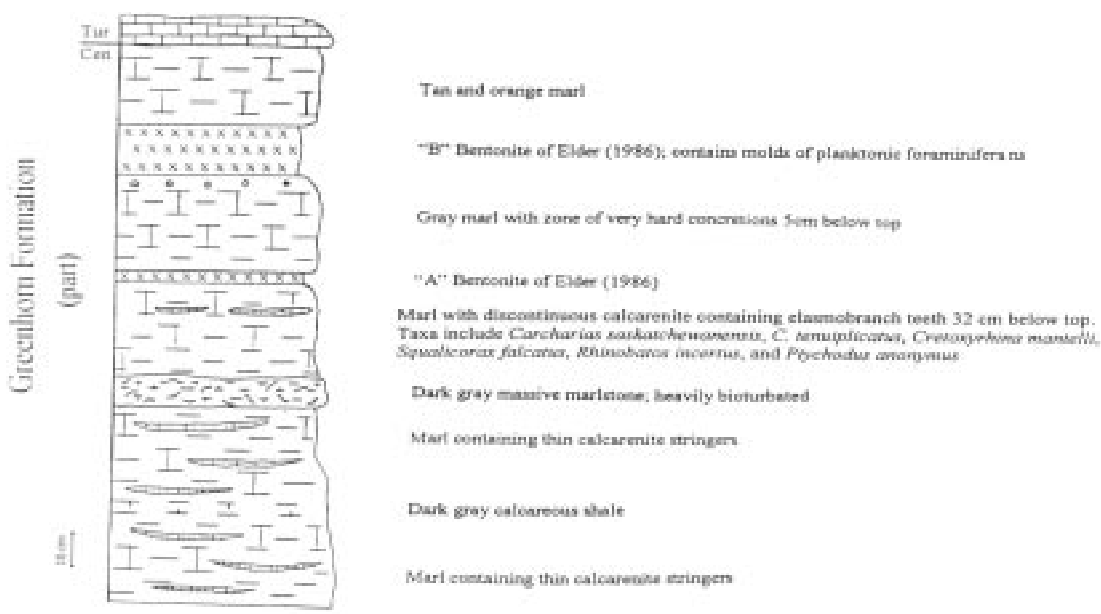


FIGURE 4. Stratigraphic section of the middle portion of the Greenhorn Formation found at the southern end of AR. The Cenomanian (Cen)-Turonian (Tur) boundary is extrapolated from the Hot Springs, Fall River Co., SD site of Elder (1986). This section is within the *Sciponoceras gracile* Biozone (late late Cenomanian age).

The Greenhorn Formation of western South Dakota shares many ammonite biozones with the principal reference section in southern Colorado near Pueblo. In the northern Black Hills the basal bed of the formation is in the *Dunveganoceras pondi* Biozone that is early late Cenomanian in age, whereas the uppermost beds are in the *Collignoniceras woollgari* Biozone of early middle Turonian age (Obradovich 1993). In the southern Black Hills the basal portion of the OLM is found in the *Plesiacanthoceras wyomingense* Biozone, indicating a late middle Cenomanian age (Obradovich 1993). In the northern Black Hills, this ammonite is found in the Belle Fourche Shale, 5 m below the basal Greenhorn beds. The base of the Greenhorn Formation is therefore older in the southern Black Hills than it is to the north. In the southern Black Hills the top of the formation is also located in the *Collignoniceras woollgari* Biozone. Based on this ammonite zonation, the age of the Greenhorn Formation in Western South Dakota is considered to be late middle Cenomanian to early middle Turonian.

Although elasmobranch fossils were collected from various locations in the Black Hills region of South Dakota and Wyoming, this report focuses on three particularly important areas (Figure 1). The Greenhorn Formation is exposed around nearly the entire perimeter of BFR in Butte County. Excel-

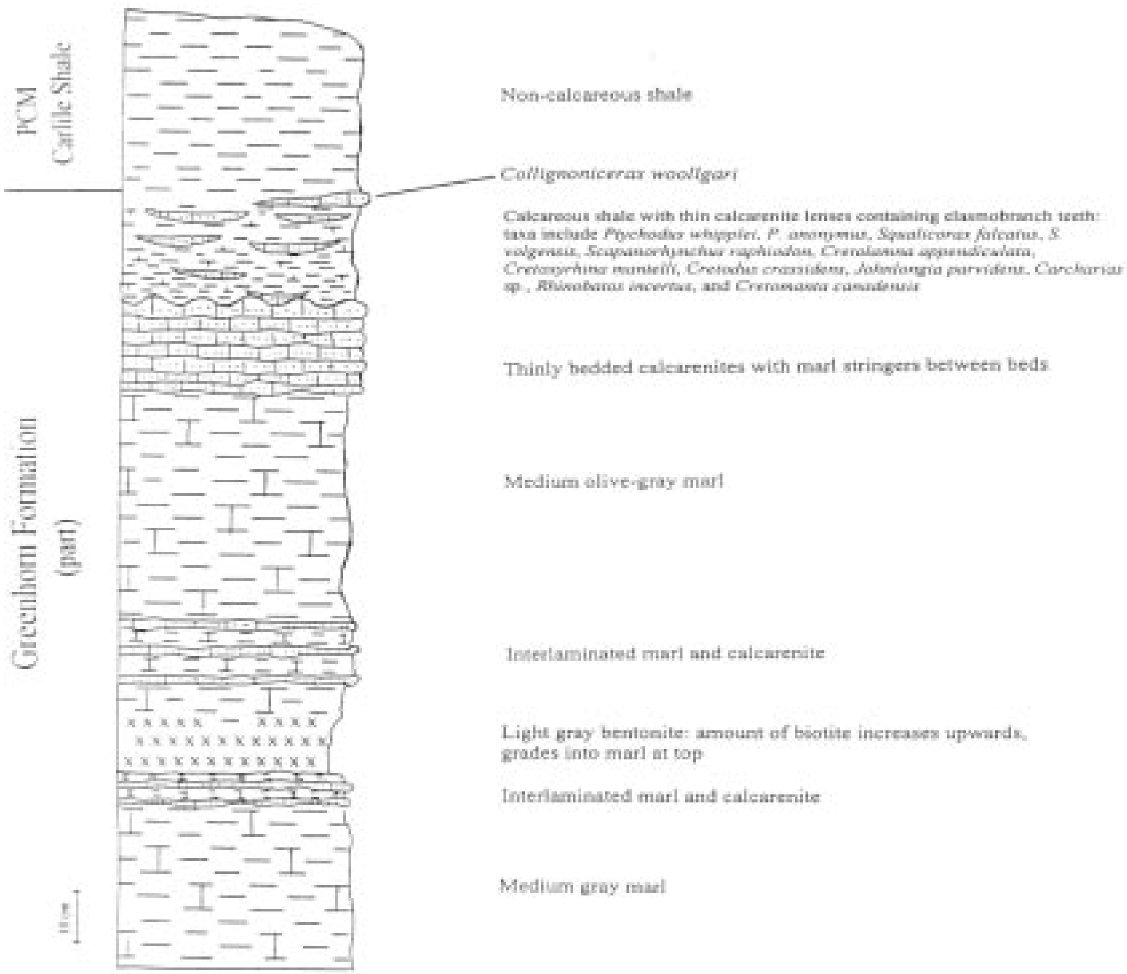


FIGURE 5. Stratigraphic section of the Greenhorn Formation/Carlile Shale contact exposed in the northwest portion of BFR. Though not clearly defined, an unconformity may exist between calcareous rocks of the Greenhorn Formation and non-calcareous rocks of the Pool Creek Member (PCM).

lent exposures of the base of the OLM are found at the southern end, whereas the Greenhorn/Carlile Shale contact is located in the northern end. Nearly the entire Greenhorn Formation is exposed in the southern portion of AR, as well as areas around Edgemont, both in Fall River County. Precise geographic information is on file at SDSM.

METHODS

Fossiliferous rocks were disaggregated using a 10% acetic acid solution. The concentrate was soaked in water to remove calcium acetate residue, then screened with 0.3 mm sieves. The remaining material was dried and sorted with a binocular microscope. Macrovertebrates found as surface float were collected after their position was noted. Stratigraphic sections were measured using combinations of Jacob's staff, tape measure, and Brunton compass. The tooth illustrations were drawn freehand or traced from photographs. *Ptychodus* teeth were cast in plaster before being photographed. The teeth of *P. whipplei* and *P.* sp. described in this report were not available for illustration, so similar teeth from the late middle Turonian Pool Creek and late Turonian Turner Sandy members of the Carlile Shale have been substituted as representative specimens. Systematic paleontology and tooth terminology generally follows Cappetta (1987) and Welton and Farish (1993).

SYSTEMATIC PALEONTOLOGY

Superfamily Hybodontoidea Zangerl, 1981

Family Ptychodontidae Jaekel, 1898

Genus *Ptychodus* Agassiz, 1835

Ptychodus anonymus **Williston, 1900**
(Figure 6, A-B)

Referred specimens – From SDSM V942: SDSM 34932, two medial teeth, SDSM 34933, two lateral teeth, SDSM 34934, posterior tooth, SDSM 35297, anterolateral tooth, SDSM 35309, medial tooth, all found as float derived from the base of the OLM; SDSM 35312, lower medial tooth, SDSM 35313, 11 teeth, all found as float 2 m above the base of the OLM. From SDSM V943: SDSM 35301, two posterior teeth from basal OLM. From SDSM V944: SDSM 34922, two anterior teeth, SDSM 35239, high-crowned variant, SDSM 35240, three teeth, all float derived from basal OLM; SDSM 31256, 19 teeth from 0.15 m below the "A" bentonite of Elder (1986); SDSM 35247, distal lateral tooth from basal OLM; SDSM 35249, 23 teeth found as float 2.5m above base of OLM; SDSM 35252, two teeth from basal OLM; SDSM 35259, two teeth as float from base of OLM; SDSM 35282, 15 teeth as float from one meter above base of OLM; SDSM 35278, 22 teeth found as float 2 m above base of OLM; SDSM 35289, tooth as float 0.3 m below third thick bentonite within the formation; SDSM 35294, eight teeth as float from within basal meter of OLM; SDSM 35295, posterior tooth as float 12 m above base of Greenhorn Formation; SDSM 35539, two anterior teeth, SDSM 35540, two posterior teeth, SDSM 35544, two anterior teeth, SDSM 35545, two posterior teeth, all as float just below "A" bentonite of Elder (1986). From SDSM V945: SDSM 35257, three teeth, SDSM 35262, two distal lateral teeth, all from 12 m below ledge-forming limestones of upper Greenhorn Formation. From SDSM V948: SDSM 35268, 13 teeth found as float from basal OLM; SDSM 35270, three teeth as float within basal 2.5 m of OLM. From SDSM V9415: SDSM 35272, four teeth, SDSM 35274, lateral tooth, all from calcarenite 0.7 m above "X" bentonite. From SDSM V9533: SDSM 34923, two anterior teeth, SDSM 35594, 34 posterior teeth, SDSM 35601, anterior tooth, all as float from basal OLM. From SDSM V9534, SDSM 35315, two teeth as float from upper Greenhorn Formation. SDSM V9536: SDSM 35322, five teeth, SDSM 35323, one tooth, SDSM 35637, 18 teeth, all as float from basal OLM. From SDSM V9537: SDSM 35326, eight teeth from calcarenite 1.5 m above "X" bentonite. From SDSM V9538: SDSM 35602, seven teeth as float from basal OLM. From SDSM V9624: SDSM 35577, two anterior teeth from calcarenites one meter below contact with Carlile Shale.

Description – Anterior teeth average 1 cm in greatest width and have a high, rounded cusp. The transition from cusp to a marginal shelf is smooth and steeply sloping. Eight to twelve transverse ridges extend from the base of the cusp across the apex. These may be straight or sinuous, and curl, bifurcate, and anastomose at their distal ends. The marginal area bulges anteriorly and is covered with a granular pattern or very fine, discontinuous concentric ridges.

Lateral teeth have a weakly developed cusp that is offset distally, whereas the crowns of posterior teeth are flat or nearly so. Transverse ridges may be straight, concentric, bifurcating, or any combination, and generally extend from one end of the crown to the other.

Discussion – *P. anonymus* is found in Cenomanian to Turonian rocks throughout the Western Inerior of the U.S. (Evetts 1979; Shimada and Martin 1993; Welton and Farish 1993; Wolberg 1985). Meyer (1974) reported a late Cenomanian to early Coniacian range for the species in the Gulf Coast area.

The tooth morphology of *P. anonymus* varies greatly, reflecting monognathic and probably dignathic heterodonty. Meyer (1974) erected what he thought were two stratigraphically distinct subspecies, *P. anonymus anonymus* and *P. a. blechroconus* (p. 48 Fig. 12, a-d; p. 52 Fig.13, a-d). Though they may be stratigraphically distinct elsewhere, both types can be found in basal rocks of the OLM, and we believe these represent morphological variation within a single taxon.

Ptychodus decurrens Agassiz, 1843
(Figure 6, C-D)

Referred specimens – From SDSM V945: SDSM 35255, incomplete tooth 11 m below top of ledge-forming limestone of upper Greenhorn. From SDSM V9532: SDSM 34935, anterior tooth found at base of ledge-forming limestone of upper Greenhorn Formation.

Description – The anterior tooth is large and mesiodistally elongate. The crown is weakly inflated but with no development of a cusp. Eleven coarse, straight to sinuous transverse ridges cross the medial area of the crown and are associated with rugose ornamentation. The ridges abruptly become much finer on the marginal area and they bifurcate distally, reaching the crown perimeter. Anterior and posterior margins bear fine bifurcating longitudinal ridges. As in all *Ptychodus* teeth, the crown overhangs the root.

Discussion – Teeth of *P. decurrens* are flat or weakly inflated, which distinguishes them from high-crowned species such as *P. mammilaris*, *P. anonymus*, and *P. occidentalis*. The transverse ridges are more robust than in *P. occidentalis*, and there is also an abrupt decrease in ridge size at the beginning of the marginal area. Teeth of *P. decurrens* differ from another low-crowned taxon, *P. polygyrus*, in that the transverse ridges do not have a concentric pattern.

Ptychodus occidentalis Leidy, 1868
(Figure 6, E-G)

Referred Specimens – From SDSM V942: SDSM 35314, five teeth, SDSM 34922, lateral tooth, all float 2 m above the base of the OLM. From SDSM V943: SDSM 35299, juvenile upper medial tooth, basal calcarenite of OLM. From SDSM V944: SDSM 31263, anterior tooth, SDSM 34925, three teeth, SDSM 32520, two posterior teeth, all as float from basal 3 m of OLM; SDSM 35260, posterior tooth as float in lower 3 m of OLM; SDSM 35283, five teeth as float 1 m above base of OLM; SDSM 35286, two teeth as float 2 m above base of OLM; SDSM 35293, four teeth as float in basal meter of OLM; SDSM 35296, incomplete tooth as float 12 m above base of Greenhorn Formation. From SDSM V948: SDSM 35264, anterolateral tooth, SDSM 35265, two posterior teeth, SDSM 35266, two upper medial teeth, SDSM 35267, lower medial tooth, all as float from basal calcarenites of OLM; SDSM 35269, medial tooth as float 2.5 m above base of OLM. From SDSM V9415: SDSM 35273, two teeth, SDSM 35276, medial tooth, all from calcarenite 0.7 m above "X" bentonite. From SDSM V9536: SDSM 3521, medial tooth and incomplete lateral tooth, all as float from basal OLM.

Description – Lower medial teeth are anterioposteriorly elongate, mesiodistally narrow, with a nearly flat crown in which the anterior margin greatly overhangs the root (Figure

6, F). Ornamentation consists of very fine transverse ridges that curl at their distal ends, and the marginal area has even finer, discontinuous ridges. Upper medial teeth can be quite large, reaching 4.5 cm in length and 4 cm in total height (Figure 6, E). The crown is symmetrical and very high, with little or no development of a cusp. The transition from margin to crown apex forms nearly a straight, steep line. Five to 13 fine, sinuous, often discontinuous ridges cross the cusp apex. These ridges bifurcate and anastomose distally, becoming finer until they reach the crown perimeter. Ornamentation on the anterior and posterior portions of the teeth consists of very fine longitudinal ridges that bifurcate and anastomose distally.

Lateral teeth become lower crowned, and the inflation also becomes offset distally (Figure 6, G). Ornamentation is similar to that of anterior teeth, but the number of transverse ridges is reduced to less than ten.

Posterior teeth have a rhombic occlusal outline, and the crown is flat. Ornamentation is as in anterior and lateral teeth, but the number of transverse ridges is reduced to seven or less.

Discussion – Variations in the thickness of the crown and development of a marginal shelf in some medial and anterior teeth may reflect dignathic heterodonty, although the possibility of sexual dimorphism cannot be ruled out.

Although crown ornamentation of *P. occidentalis* is similar to *P. decurrens*, upper medial and anterior teeth of *P. occidentalis* are much more inflated. Asymmetrically inflated lateral teeth are also characteristic of *P. occidentalis*. Lateral and posterior teeth of *P. decurrens* can be distinguished from posterior teeth of *P. occidentalis* in having more robust transverse ridges.

P*tychodus whipplei* Marcou, 1858
(Figure 6, H-J)

Referred specimens – From SDSM V9624: SDSM 35583, lateral tooth, SDSM 35590, anterior tooth, both from uppermost Greenhorn Formation, within one meter below the Carlile Shale contact.

Description – The anterior tooth measures 1 cm in width and is nearly symmetrical. The crown possesses a tall, laterally compressed central cusp that meets the marginal area at nearly a right angle. Five coarse transverse ridges are restricted to the cusp. Extremely fine ridges form a concentric pattern on the marginal area. Conspicuous wear facets are located on the cusp and the mesial and distal edges of the marginal area. The crown overhangs the root, especially at the anterior end.

The lateral tooth is highly asymmetrical with a distally placed, distally inclined cusp. The cusp is tall, laterally compressed with four coarse transverse ridges that do not enter the marginal area. The transition from cusp to marginal area is steeply sloping, and the mesial marginal area is longer than the distal marginal area. Marginal ornamentation consists of very fine, discontinuous concentric ridges.

Discussion – Anterior teeth of *P. whipplei* can be distinguished from *P. anonymus* in that the cusp is laterally compressed and has a smaller diameter. In lateral teeth, the cusp is narrower than in *P. anonymus*, and the anterior crown margin is often irregular, not flat. The number of transverse ridges is reduced, with only two to nine as opposed to eight to twelve. Also, these ridges do not curl around the base of the cusp as in *P. anonymus*.

P. whipplei is often a common constituent of Turonian rocks of the Western Interior (Cappetta 1973; Edwards 1976; Meyer 1974; Williamson et al. 1993; Wolberg 1985). However, its distribution appears to have been restricted to this area. Williamson et al. (1993) indicated that this taxon preferred deep-water environments, but in South Dakota it is only known from shallow-water rocks of the Greenhorn Formation and Carlile Shale (see Cappetta 1973; Cicimurri 1998). This suggests that *P. whipplei* was able to inhabit a wide range of habitats, so its absence from areas outside the Western Interior of North America is difficult to explain.

***Ptychodus* sp.**
(Figure 6, K-N)

Referred specimens – From SDSM V9624: SDSM 35587, eight teeth from uppermost Greenhorn, within one meter below the contact with the Carlile Shale.

Discussion – The teeth are small, less than 1 cm in greatest dimension. Anterior teeth have a high, conical crown that is slightly laterally compressed. There is no clear transition between a cusp and marginal area in anterior and anterolateral teeth. Four to seven straight or chevron-shaped transverse ridges cross the apex, but are often restricted to the upper third to half of the crown. These ridges may coalesce at the apex, resembling a radiating pattern. Very fine longitudinal ridges are found on the anterior and posterior faces of the crown. Ornamentation on the marginal area consists of very fine, short, interconnected ridges or granules that have a concentric pattern.

Lateral and posterior teeth have a lower crown that becomes more distally inclined towards the back of the jaw. Ornamentation is similar to that of anterior teeth.

Discussion – Teeth with this morphology also occur in the PCM of South Dakota and the Boquillas Formation of Texas (Cicimurri and Bell 1996; Cicimurri 1998). The teeth appear to be close to *P. mortoni* in having a high, conical cusp, with the occasional development of radiating ridges on the crown. These characteristics are unlike all other *Ptychodus* species (see Welton and Farish 1993), and we believe this form represents a new taxon that is closely related to *P. mortoni*. The taxon questionably occurs in the OLM (based on abraded specimens).

Order Lamniformes Berg, 1958
Family Anacoracidae Casier, 1947
Genus *Squalicorax* Whitley, 1939
***Squalicorax curvatus* Williston, 1900**
(Figure 7, A)

Referred specimens – From SDSM V942: SDSM 35310, three teeth as float from basal OLM. From SDSM V944: SDSM 35241, 43 teeth, SDSM 35244, six teeth, all from 0.15 m below the "A" bentonite of Elder (1986); SDSM 31262, incomplete tooth as float 3.5 m above the base of the OLM; SDSM 35284, three teeth as float from basal meter of OLM; SDSM 35290, two teeth as float from 0.3 m below the third thick bentonite of the Greenhorn Formation; SDSM 35291, two teeth within basal meter of OLM. From SDSM V946: SDSM 35304, 16 teeth as float from near "A" bentonite of Elder (1986). From SDSM V948: SDSM 35271, incomplete tooth as float 2.5 m above base of Greenhorn Formation. From SDSM V9415: SDSM 35273, four teeth from calcarenite 0.7 m above "X" bentonite. From SDSM V9533: SDSM 35562, 15 teeth from basal calcarenites of OLM. From SDSM V9536: SDSM 35546, 19 teeth, SDSM 35639, seven teeth, all from basal calcarenites of OLM. From SDSM V9537: SDSM 34926, two teeth, SDSM 35557, 46 teeth, all from calcarenite 1.5 m above "X" bentonite. From SDSM V9538, SDSM 35553, anterolateral tooth from basal OLM calcarenites.

Description – The teeth are rather small (8 mm or less) with a sharply distally inclined cusp. The crown is thick due to a weakly to moderately convex labial face and a strongly convex lingual face. The mesial cutting edge is finely serrated, long, and may be straight, convex, or sinuous. The distal cutting edge is also serrated, but less than half as long as the mesial edge. A distal blade is low, finely serrated, and intersects the distal cutting edge at a sharp angle. The root is low when viewed lingually and consists of two short, diverging, rounded lobes.

Discussion – These specimens display a high degree of variability, and Cenomanian anacoracid teeth have variously been referred to *S. baharijensis* and *S. curvatus* (Welton and Farish 1993; Cappetta and Case 1999). We identify the specimens described above as *S. curvatus* based on the convex labial crown face, which follows the original description of the species by Williston (1900).

Squalicorax falcatus Agassiz, 1843
(Figure 7, B)

Referred specimens – From SDSM V9623: SDSM 35582, ten teeth from uppermost Greenhorn Formation, within one m of the Carlile Shale contact. From SDSM V9624: SDSM 35593, two teeth from same horizon as previous specimens.

Description – Teeth reach up to 1.5 cm in greatest dimension. Anterior teeth are high-crowned with a distally inclined cusp. The labial crown face is flat, whereas the lingual face is convex. The serrated mesial cutting edge is straight or weakly convex, but the distal cutting edge is shorter, convex and finely serrated. A distal blade is low, finely serrated, and meets the base of the distal cutting edge at an acute angle (obtuse in some anterior teeth). The root is moderately high when viewed lingually, with short, diverging, somewhat rounded to rectangular lobes (as seen in lateral teeth of *Cretolamna*).

Lateral and posterior teeth have a lower crown and more distally inclined cusp. The mesial cutting edge is often sinuous. The root is also lower with thin, rounded lobes.

Discussion – Teeth attributed to *S. falcatus* exhibit a high degree of variation, and the taxon has been reported as having a Cenomanian to Campanian range (Welton and Farish 1993; Martin et al. 1998). In recent years there have been suggestions and attempts to split *S. falcatus* into separate, time-restricted species (Cappetta and Case 1999). We advise against this splitting because without numerous complete dentitions, it is uncertain that the variation within *S. falcatus* represents monognathic, dignathic, ontogenetic or sexual heterodonty, or if more than one species is actually represented. However, we believe that the teeth referred to *S. falcatus* by Martin et al. (1998) actually represent lateral teeth of *S. kaupi* (i.e. early forms of *S. kaupi* retain an *S. falcatus* morphology in lateral and posterior row groups).

Squalicorax volgensis
(Gluckman *in* Gluckman and Shvazhaite), 1971
(Figure 7, C)

Referred specimens – From SDSM V946: SDSM 35303, two teeth as float from near "A" bentonite of Elder (1986). From SDSM V9533: SDSM 35563, one tooth from basal OLM. From SDSM V9536: SDSM 35320, two teeth from basal OLM. From SDSM V9537: SDSM 35558, two teeth from calcarenite 1.5 m above "X" bentonite. From SDSM V9623: SDSM 35574, 37 teeth from uppermost Greenhorn Formation, within 1 m of the contact with the Carlile Shale. From SDSM V9624: SDSM 35588, six teeth from same stratigraphic horizon as SDSM 35574.

Description – Symphyseal teeth are nearly symmetrical with a tall, narrow cusp and one pair of low, rounded "cusplets" that are not detached from the cusp. The lingual crown face is very convex and smooth, whereas the labial face is convex near the apex, but becomes flat or concave near the crown foot. Mesial and distal blades are smooth, sharp, but do not reach the apex. The root is narrow with short, diverging lobes.

Anterior teeth are mesiodistally narrow with a tall, distally inclined cusp. The mesial cutting edge is long and may be convex, straight, or slightly sinuous. The distal cutting edge is half the length of the mesial edge and may be convex, straight, or even concave. A distal blade is short, very convex, and separated from the distal cutting edge by a notch in the enameloid (sometimes nearly forming a distinct cusplet). The cutting edges are often smooth, but fine serrations may be found on the lower portion of the mesial edge. The root is bilobate with short, sub-rectangular lobes.

Lateral and posterior teeth are broader than anteriors, but lower crowned and sharply distally inclined. The mesial cutting edge is long and convex (especially evident in posterior teeth), whereas the distal edge is short and convex. The distal blade varies in length, but it is convex and separated from the distal cutting edge by a deep notch (sometimes resembling a lateral cusplet). Cutting edges are generally unserrated, but the mesial edge may be weakly serrated on the lower portion. The root is bilobate, with the mesial lobe often longer than the distal lobe.

Discussion – This taxon appears to be less derived than other temporally equivalent or younger species of *Squalicorax* in the lack of or weak development of serrations. Morphological variations such as the shape of the mesial cutting edge, degree of distal inclination of the cusp, and variation of the serration pattern indicate both monognathic and dignathic heterodonty within an individual, as has been noted by Welton and Farish (1993). Siverson (1996) even suggested the possibility of ontogenetic heterodonty, indicating that the "*S. volgensis*" morphology represented juvenile teeth of *S. curvatus*/*S. falcatus*. We believe *S. volgensis* is a distinct taxon because even the smallest teeth of *S. curvatus* and *S. falcatus* are serrated, whereas even large teeth of *S. volgensis* can be unserrated.

Family Cretoxyrhinidae Gluckman, 1958
Genus *Cretodus* Sokolov, 1965
***Cretodus crassidens* (Dixon), 1850**
(Figure 7, D-E)

Referred specimen – From SDSM V9624: SDSM 35591, incomplete anterolateral tooth as float from uppermost part of Greenhorn Formation, within one meter below the contact with the Carlile Shale.

Description – The tooth is large, measuring 3cm in preserved height. The crown is tall, broad-based, and slightly distally recurved. The labial crown face is flat and smooth, whereas the lingual crown face is highly convex. The root is incomplete, but the lingual boss is massive and shelf-like.

Discussion – Unfortunately the specimen is highly weathered. However, the massive lingual boss distinguishes this tooth from *Cretoxyrhina*. The tooth is larger and more massive than teeth of *Cretoxyrhina* and *Cretolamna* from the same deposits. The lack of labial and lingual longitudinal ridges separate SDSM 35591 from *C. semiplicatus*.

This specimen represents the earliest occurrence of *C. crassidens* in the Black Hills Region. It is relatively common in the Pool Creek and Turner Sandy members of the Carlile Shale of South Dakota (Cappetta 1973; Cicimurri 1998).

***Cretodus semiplicatus* (Munster) *in* Agassiz, 1843**
(Figure 7, F-G)

Referred specimen – AMM98.1.2, incomplete anterior tooth from basal calcarenites of OLM, near Fruitdale, Butte Co., SD.

Description – The tooth is large, measuring nearly 3cm in preserved height. It is symmetrical with a tall, rather narrow, sharply pointed cusp. The labial crown face is slightly convex, with several very short longitudinal ridges located at the crown foot. The lingual face is highly convex, with conspicuous longitudinal ridges extending more than half the length of the crown. The root appears to have been symmetrical as well, with large, diverging lobes and a large lingual boss.

Discussion – Although incomplete, this specimen can be distinguished from *C. crassidens* by longer longitudinal ridges on the lingual crown face. This type of ornamentation is not seen in *Cretolamna* or *Cretoxyrhina*.

AMM98.1.2 represents the youngest occurrence of *C. semiplicatus* in the Black Hills region. It appears to be somewhat more common in older rocks of the Mowry Shale and Belle Fourche Shale (Cicimurri 1998; Cicimurri in press).

Genus *Cretolamna* Gluckman, 1958
***Cretolamna appendiculata* Agassiz, 1843**
(Figure 7, H)

Referred specimens – From SDSM V 942: SDSM 35308, lateral tooth as float from basal OLM. From SDSM V944: SDSM 35280, lateral tooth as float one meter above base of OLM. SDSM V9533: SDSM 35597, three incomplete teeth as float from basal OLM. From SDSM V9535: SDSM 35317, lateral tooth as float 30m below "B" bentonite of Elder (1986). From SDSM V9536: SDSM 35324, two lateral teeth from basal OLM calcarenites. From SDSM V9537: SDSM 35330, lateral tooth from calcarenite 1.5 m above "X" bentonite. From SDSM V9623: SDSM 35578, lateral tooth from uppermost Greenhorn Formation, within one meter below the Carlile Shale contact. From SDSM V9624: SDSM 35592, incomplete tooth from same horizon as previous specimen.

Description – The teeth are of moderate size, not larger than 2.5 cm in total height. Anterior teeth are symmetrical with a tall, erect, slightly sigmoidal crown. The labial crown face is flat, whereas the lingual face is convex. There is no crown ornamentation, and one pair of large, diverging lateral cusplets straddles the central cusp. The cutting edge is sharp, smooth and continuous across the central cusp. The root is bilobate with rather short, rounded lobes and a rounded lingual boss.

Lateral and posterior teeth are lower crowned, with a broader, recurved cusp. Lateral cusplets are not as divergent as in anterior teeth, but are much broader. Root lobes are short, rectangular, and labio-lingually thin.

Discussion – The taxon *Cretolamna* (especially *C. appendiculata*) has an unusually long temporal range, having been reported from early Cretaceous-middle Paleogene (Eocene) rocks from around the world (Cappetta 1987; Kent 1999). Teeth of this shark can be distinguished from the cretoxyrhinids *Cretoxyrhina* and *Paraisurus* in having large lateral cusplets, and from *Leptostyrax*, *Cretodus semiplicatus*, and some *Protolamna* in lacking crown ornamentation (Welton and Farish 1993, Cappetta and Case 1999).

Genus *Cretoxyrhina* Gluckman, 1958
***Cretoxyrhina mantelli* (Agassiz), 1843**
(Figure 7, I-K)

Referred specimens – From SDSM V942: SDSM 35298, incomplete tooth from basal OLM; SDSM 35311, five incomplete teeth as float two meters above the base of the OLM. From SDSM V944: SDSM 34942, posterior tooth from basal OLM; SDSM 35238, lateral tooth as float near base of OLM; SDSM 35241, 24 teeth, including juveniles, SDSM 35242, 29 teeth, all from 0.15 m below "A" bentonite of Elder (1986). From SDSM V945: SDSM 35256, three incomplete teeth from 11 m below top of ledge-forming limestone at top of Greenhorn Formation; SDSM 35258, juvenile tooth from 12 m below top of ledge-forming limestone of upper Greenhorn; SDSM 35261, three incomplete teeth as float 11 meters below ledge-forming limestone of upper Greenhorn; SDSM 35263, tooth in matrix from 1.5 m below top of Greenhorn caprock. From SDSM V946: SDSM 35302, seven teeth, SDSM 35306, three teeth, all as float near "A" bentonite of Elder (1986); SDSM 31261, incomplete tooth as float from ledge-forming limestone of upper Greenhorn Formation; SDSM 35248, eight teeth, SDSM 35253, 11 incomplete teeth, all as float 2 m above base of OLM; SDSM 35251, three teeth as float 0.61 m above base of OLM; SDSM 35281, six incomplete teeth, SDSM 35292, three incomplete teeth, all as float one meter above base of OLM; SDSM 35285, ten teeth as float 2 m above base of OLM; SDSM 35288, two incomplete teeth as float 0.3 m below third thick bentonite of basal Greenhorn Formation; SDSM 35541, incomplete tooth, SDSM 35543, anterior tooth, all from near "A" bentonite of Elder (1986). From SDSM V9415: SDSM 35278, three teeth from calcarenite 0.7 m above "X" bentonite. From SDSM V9533: SDSM 35598, eight anterior teeth, SDSM 35599, three lateral teeth, SDSM 35600, five posterior teeth, all float from basal calcarenites of OLM. From SDSM V9534: SDSM 35316, three anterior teeth as float from upper Greenhorn. From SDSM V9535: SDSM 34941, anterior tooth as float from basal OLM; SDSM 35318, three teeth as float 30 m below "A" bentonite of Elder (1986). From SDSM V9536: SDSM 35319, 11 teeth, two incomplete teeth, all float from basal calcarenites of OLM. From SDSM V9537: SDSM 35325, four teeth, SDSM 35328, three juvenile teeth, all from calcarenite 1.5 m above "X" bentonite. From SDSM V9538: SDSM 35603, five teeth from basal OLM. From SDSM V9623: SDSM 35580, six teeth from uppermost Greenhorn Formation, within one meter below contact with Carlile Shale. From SDSM V9624: SDSM 35573, nine teeth from same horizon as SDSM 35580.

Description – Teeth can attain 3 cm in total height. Anterior teeth have a tall, narrow, slightly sigmoidal crown that may be distally inclined. The labial face is flat, whereas the lingual face is convex. There is no ornamentation, and cutting edges are smooth and sharp across the entire crown. The root is massive and often asymmetrical with a longer mesial lobe.

Lateral teeth are broader and lower crowned than anterior teeth. A small pair of weakly developed lateral cusplets may be found on some teeth. Root lobes are short and rectangular. Posterior teeth are small, low crowned, with a pair of lateral cusplets. Root lobes are short and rounded.

Juvenile teeth are small and gracile, with a well-developed pair of lateral cusplets. The root is delicate, with long and narrow lobes.

Discussion – Teeth of *Cretoxyrhina* are very common in the Greenhorn Formation of South Dakota. Indeed, the taxon had a worldwide distribution during the late Cretaceous (Cappetta 1987; Siverson 1996). The teeth of this shark differ from *Cretolamna* in its more robust proportions and the lack of lateral cusplets on anterior and most lateral teeth. The taxon can be distinguished from *Cretodus* in the lack of longitudinal ridges on the cusp.

This taxon is uncommon in the overlying PCM of the Carlile Shale (Cicimurri 1998), and it is absent altogether in the Turner Sandy Member (Cappetta 1973; Evetts 1979). It is thought that *Cretoxyrhina* inhabited mostly deep-water environments (Williamson et al. 1993; Shimada 1994; Schwimmer 2000). As noted above, we document this shark in shallow-water rocks of the Greenhorn Formation and PCM. The rocks of the Turner Sandy Member were deposited in an upper shoreface environment dominated by wave-generated and tidal currents (Sawyer 1990). The absence of *Cretoxyrhina* in these rocks suggests the water was too shallow for this shark, and its niche seems to have been occupied by *Cretodus crassidens* (see Cappetta 1973).

Family Mitsukurinidae Jordan, 1898
Genus *Scapanorhynchus* Woodward, 1889
***Scapanorhynchus raphiodon* (Agassiz), 1844**
(Figure 7, L)

Referred specimens – From SDSM V9623: SDSM 35579, 26 teeth from uppermost Greenhorn Formation, within one m below the contact with the Carlile Shale. From SDSM V 9624: SDSM 35589, four incomplete teeth from same horizon as previous specimens.

Description – Teeth are of moderate size, up to 2 cm in total height. Lower anterior teeth have a tall, slender cusp with a sigmoidal profile. The labial crown face is flat and smooth, and the enameloid extends basally onto the root lobes. The lingual face is convex and bears fine longitudinal striations that do not reach the cusp apex. Lateral cusplets are generally absent, but a single pair of very small cusplets was found on some teeth. The root is bilobate with long, thin lobes. A large lingual boss is bisected by a deep nutritive groove.

Lateral teeth are wide basally and distally inclined. The cusp is labio-lingually compressed with a cutting edge that is continuous along the entire cusp. The labial face is smooth, whereas the lingual face may have very fine longitudinal striations. At least one pair of lateral cusplets is always present. The lingual root boss is reduced, but the nutritive groove remains. The root itself becomes labio-lingually flattened, and the lobes are sub-rectangular.

Discussion – The specimens described here represent the earliest occurrence of the taxon in the Black Hills. This shark was also common in the Pool Creek and Turner Sandy members of the Carlile Shale (Cappetta 1973; Cicimurri 1998), as well as temporally equivalent rocks throughout the

Western Interior of North America (Edwards 1976; Wolberg 1985; Williamson et al. 1993; Cicimurri and Bell 1996).

Family Odontaspididae Muller and Henle, 1839
Genus *Carcharias* Rafinesque, 1810
***Carcharias* aff. *amonensis* (Cappetta and Case), 1975**
(Figure 7, M)

Referred specimen – From SDSM V9533: SDSM 35566, one tooth from basal calcarenite of OLM.

Description – The tooth is small, measuring only 4 mm in total height. It is slightly asymmetrical with a distally inclined cusp. The cusp is broad-based but tapers to a sharp point. The labial face is flat and the lingual face is convex, with both faces being unornamented. A single pair of low, broad, sharply pointed cusplets flanks the central cusp. The root is broadly bilobate with short, thin, rounded lobes. A lingual nutritive groove bisects the root.

Discussion – Though SDSM 35566 is abraded, there is no indication of crown ornamentation, and the lateral cusplets are low and broadly triangular. For these reasons we tentatively refer this tooth to *C. amonensis*, rather than *C. saskatchewanensis* or *C. tenuiplicatus* (see Fig. 7, M-O). A tooth referred to this taxon by Cicimurri (1998) from the uppermost Greenhorn has been reassigned to *Carcharias* sp. (of this report). *C. amonensis* has an early to late Cenomanian range in South Dakota, and it is especially abundant in middle Cenomanian rocks of the Belle Fourche Shale (Cicimurri 2001). This shark is also commonly found in Cenomanian rocks of Kansas and Texas (Shimada and Martin 1993; Welton and Farish 1993; Cappetta and Case 1999).

***Carcharias saskatchewanensis* Case et al., 1990**
(Figure 7, N)

Referred specimens – From SDSM V944: SDSM 35246, 77 teeth from 0.15 m below the "A" bentonite of Elder (1986); SDSM 35254, one tooth as float 0.6 m above base of the OLM. From SDSM V946: SDSM 35307, four teeth as float near "A" bentonite of Elder (1986). From SDSM V9415: SDSM 35279, 31 teeth from calcarenite 0.7 m above "X" bentonite. From SDSM V9533: SDSM 35564, 69 teeth from basal OLM calcarenites. From SDSM V9536: SDSM 34927, two anterior teeth, SDSM 34928, two lateral teeth, SDSM 35547 nine teeth, SDSM 35550, 28 teeth, all from basal calcarenites of OLM. From SDSM V9537: SDSM 35559, 47 teeth from calcarenite 1.5 m above "X" bentonite. From SDSM V9538: SDSM 35555, three teeth from basal OLM.

Description – Teeth are very small, measuring 4 mm or less in total height. Anterior teeth have a tall, sharply pointed central cusp that is flanked by a pair of needle-like lateral cusplets. The cusplets are closely connected to the central cusp. Labial and lingual crown faces are convex (lingual face more so) and unornamented. The cutting edge is smooth, sharp, and continuous across the cusp and lateral cusplets. Root lobes are short, rounded, and divergent, overhung by a prominent labial shelf at the base of the crown.

Lateral and posterior teeth become low crowned and more distally inclined. The labial and lingual crown faces are convex, and the labial face often bears a few short longitudinal ridges. Generally only a single pair of sharp lateral cusplets are tightly connected to the central cusp. The root has very short, widely separated lobes of unequal length. A deep nutritive groove bisects the lingual boss of all teeth.

Discussion – This species was reported by Case et al. (1990) from Saskatchewan, Canada. Teeth have also been collected from the Lincoln Limestone Member, Greenhorn Limestone of Kansas (Shimada and Martin 1993), and Welton and Farish (1993:91) illustrated similar teeth from Cenomanian rocks of Texas that represent shallow-water environments. This species is not known to occur in Turonian rocks.

***Carcharias tenuiplicatus* (Cappetta and Case), 1975**
(Figure 7, O-P)

Referred specimens – From SDSM V944: SDSM 35245, six teeth from 0.15 m below the "A" bentonite of Elder (1986). From SDSM V9533: SDSM 35565, six teeth from basal calcarenites of the OLM. From SDSM V9536: SDSM 35551, two teeth from basal OLM. From SDSM V9537: SDSM 34920, two teeth, SDSM 34930, three anterior teeth, SDSM 35560, nine teeth, all from calcarenite 1.5 m above the "X" bentonite.

Description – The teeth are very small, less than 5 mm in total height. Anterior teeth have an erect, sharply pointed central cusp that is flanked by at least one pair of needle-like lateral cusplets. The labial crown face is nearly flat, whereas the lingual face is convex. Coarse longitudinal ridges are found at the crown foot of the lingual face, but extend nearly to the cusp apex on the labial face. A broad labial basal shelf overhangs the root. The root is bilobate with short, widely separated, rounded lobes.

Lateral and posterior teeth are lower crowned, distally inclined, often with more pronounced labial ornamentation. Two pairs of lateral cusplets are closely associated with the central cusp (the second pair is much smaller than the first). The cutting edge is smooth and continuous across the cusp and lateral cusplets of all teeth, and the root is bisected by a deep nutritive groove.

Discussion - The tooth morphology of this taxon is similar to that of *C. saskatchewanensis*, except that all teeth bear coarse longitudinal striations on the labial face, as well as shorter ridges on the lingual face. In addition, there are generally two pairs of lateral cusplets.

This taxon is also common in Kansas and Texas, where it occurs in Cenomanian rocks representing nearshore, shallow-water environments (Shimada and Martin 1993; Welton and Farish 1993). The shark has not been reported from Turonian rocks, and this lead Cappetta and Case (1999) to rename the taxon *Cenocarcharias tenuiplicatus*. We do not agree with this reassignment and choose to retain *Carcharias*, especially because early Turonian marine rocks outside of Texas have not been adequately sampled.

Carcharias sp.
(Figure 7, Q-T)

Referred specimens – From SDSM V9623: SDSM 35584, 40 teeth from uppermost Greenhorn Formation, within one meter below the contact with the Carlile Shale.

Description – The teeth are small, not reaching 1 cm in total height. Anterior teeth have a tall, slender, slightly sigmoidal cusp. The labial face is smooth and flat, whereas the lingual face is convex and smooth. The cutting edge is sharp and continuous across the central cusp. A single pair of short, narrow, divergent lateral cusplets flanks the cusp. These are nearly detached from the central cusp when viewed labially. The root is bilobate with relatively long, narrow, rounded lobes. The lingual boss is bisected by a nutritive groove.

Lateral and posterior teeth have a broad-based, sharply pointed, recurved cusp. Teeth are unornamented with flat labial and convex lingual faces. The central cusp is flanked by a pair of low, broadly triangular, divergent lateral cusplets (a second smaller pair was found on some teeth). The root is broad but thin, bilobate with sub-rectangular lobes and a deep lingual nutritive groove.

Discussion – This tooth type also occurs in late middle Turonian rocks of the PCM of South Dakota (Cicimurri 1998). They are similar to teeth of ?*Odontaspis subulata* described by Meyer (1974) from Turonian and Coniacian rocks of Texas.

This tooth type differs from *C. amonensis* in that lateral teeth generally have only one pair of lateral cusplets, and the distal recurvature is greater than in *C. amonensis*.

Genus _Johnlongia_ Siverson, 1996
Johnlongia parvidens (Cappetta), 1973
(Figure 7, U-W)

Referred specimens – From SDSM V9623: SDSM 34937, anterior tooth, SDSM 34938, lateral tooth, SDSM 35575, ten teeth, all from uppermost Greenhorn Formation, within one meter below base of Carlile Shale. From SDSM V9624: SDSM 35586, one tooth from same horizon as previous specimens.

Description – The teeth are small, less than 1 cm in total height. Anterior teeth have a tall, slender, sigmoidal cusp. Cutting edges are sharp but restricted to the upper portion of the cusp. The crown faces are smooth, with weakly convex labial and strongly convex lingual faces. A pair of small lateral cusplets are closely connected to the central cusp. The root is unusual in having a massive lingual boss that is bisected by a large nutritive groove. Root lobes are short and rounded, asymmetrical with a longer distal lobe. Anterior teeth of juvenile individuals are identical to those of adults, except for conspicuous labial longitudinal ridges.

The lateral tooth has a broad-based cusp that quickly tapers apically. It is labio-lingually thin with a sharp, continuous cutting edge. The labial crown face bears longitudinal ridges that are restricted to the lower half of the cusp. A pair of tall, needle-like lateral cusplets are closely connected to the central cusp. In labial view, the enameloid extends nearly to the base of the root lobes. Root lobes are thin with a sub-rectangular outline.

Discussion – Cappetta (1973) originally reported *Odontaspis parvidens* from the Turner Sandy Member of the Carlile Shale, South Dakota. Siverson (1996) erected the genus *Johnlongia* to include odontaspid teeth having this unusual morphology. To date, the taxon is only known from Cenomanian rocks of Australia (Siverson 1996) and middle to late Turonian rocks of South Dakota (Cappetta 1973; Cicimurri 1998).

Order Rajiformes Berg, 1940
Family Rhinobatidae Muller and Henle, 1838
Genus _Rhinobatos_ Link, 1790
Rhinobatos incertus Cappetta, 1973
(Figure 7, X)

Referred specimens – From SDSM V944: SDSM 35243, one tooth from 1.5 m below the “A” bentonite of Elder (1986). From SDSM V9531: SDSM 35640, six teeth from calcarenites near “B” bentonite of Elder (1986). From SDSM V9533: SDSM 35595, two female teeth from basal OLM. From SDSM V9537: SDSM 35329, three teeth from 1.5 m above the “X” bentonite. From SDSM V9623: SDSM 35585, one tooth from uppermost Greenhorn Formation, within one meter below the contact with the Carlile Shale.

Description – The teeth are microscopic, no larger than 1 mm in greatest dimension. The crown is mesiodistally wide and unornamented. The labial face forms a flat to weakly convex surface, and the crown foot overhangs the root. An elongate, rounded lingual protuberance is located at the center of the crown that is flanked by a pair of shorter protuberances. Each protuberance is separated by a deep sulcus. A central cusp grades from absent to pronounced (if present it is lingually inclined). The cutting edge, if present, is restricted to the central area of the crown. The root is low with a flat to convex attachment surface. It is often divided into two triangular lobes by a deep nutritive groove. A large foramen located just below the central lingual protuberance opens into the groove. Smaller foramina may be visible on each side of the central protuberance.

Discussion – *Rhinobatos* exhibits sexual dimorphism in tooth morphology with females having low-crowned teeth, whereas male teeth possess a tall, conspicuous cusp. This characteristic probably inhibits intraspecific competition – males of a given species may have different diets than the females. Recent species of *Rhinobatos* inhabit relatively shallow coastal waters of depths less than 100 m (Ticas et al. 1997).

Elasmobranchii incertae cedis
Genus _Cretomanta_ Case et al., 1990
Cretomanta canadensis Case et al., 1990
(Figure 7, Y)

Referred specimens – From SDSM V944: SDSM 35542, three teeth from calcarenite below "A" bentonite of Elder (1986). From SDSM V946: SDSM 35305, one tooth from near "A" bentonite of Elder. From SDSM V9415: SDSM 35277, two teeth from calcarenite 0.7 m above "X" bentonite. From SDSM V9533: SDSM 35596, eight teeth from basal OLM. From SDSM V9537: SDSM 35327, 21 teeth from calcarenite 1.5 m above "X" bentonite. From SDSM V9623: SDSM V35581, four teeth from uppermost Greenhorn Formation, within one meter below the contact with the Carlile Shale.

Description – The teeth are microscopic, less than 1 mm in total height. The crown consists of a low, lingually inclined or recurved cusp that is often distally inclined as well. Labial and lingual crown faces are smooth and convex, and the labial face may bulge at the crown foot. The cusp may be conical or possess mesial and distal cutting edges. The root is globular with numerous foramina. The attachment surface is convex.

Discussion – *Cretomanta* is an enigmatic and problematic taxon. It was originally placed in Mobulidae by Case et al. (1990) based on the superficial resemblance to the Recent devil ray, *Manta*. Welton and Farish (1993) referred similar teeth to Rhincodontidae based on the superficial resemblance to the whale shark, *Rhincodon*. Because this taxon is based solely on isolated teeth, Cappetta and Case (1999) hesitated to refine its systematic classification, although they suggested that the animal fed primarily on plankton.

DISCUSSION

The Greenhorn Formation of western South Dakota has yielded a wide variety of vertebrates that includes bony fish, elasmobranchs, chelonioids, mosasauroids, pliosauroids and plesiosauroids, and a pterosaur. The greatest diversity and abundance of these taxa occurs within basal rocks of the OLM, and within calcarenites at the very top of the formation. Thirteen elasmobranch taxa were recovered from the OLM, whereas 14 were collected from the top of the formation (Table 1).

The oldest Greenhorn Formation elasmobranchs were collected from the base of the OLM at AR and Edgemont in the southern Black Hills. These rocks, as well as associated selachians such as *Carcharias* and *Rhinobatos*, indicate deposition took place in relatively shallow water (above wave base). The remains were associated with the ammonite *Plesiacanthoceras wyomingense* and are of late middle Cenomanian age (Obradovich 1993). At BFR in the northern Black Hills, this ammonite occurs within non-calcareous black shale of the Belle Fourche Shale, 5 m below the base of the Greenhorn. This illustrates nicely the diachronous nature of Greenhorn deposition, as the Greenhorn Seaway (during the late middle Cenomanian) was shallower in the southern portion of present-day South Dakota than it was 128 km to the north.

Elasmobranch fossils collected from the base of the OLM at BFR are associated with the ammonite *Dunveganoceras pondi*, indicating an early late Cenomanian age (Obradovich 1993). Although slightly younger, this assemblage is identical to that from AR. At BFR, two calcarenites are exposed at the base of the OLM, one unconformably overlying the Belle Fourche Shale, the other separated from the first by a bentonite (the calcarenites contain identical vertebrate taxa). At AR, the base of the OLM is separated from the Belle Fourche Shale by the "X" bentonite. A highly irregular surface is preserved at the top of the Belle Fourche Shale at BFR, indicating the "X" bentonite was eroded from this area prior to initial deposition of the Greenhorn Formation.

The elasmobranch assemblages from the Greenhorn Formation in South Dakota are very similar to temporally equivalent assemblages in the Western Interior of the U.S. (see Table 1 for a detailed comparison). This should not be surprising, as sharks and rays are mobile organisms that are able to radiate into areas with desirable environmental conditions.

Few selachian taxa have been recovered from the latest Cenomanian portion of the Greenhorn Formation, and no elasmobranchs were collected from the early Turonian portion. This is in part due to the lack of exposures and/or fossiliferous rocks. The fossils that we collected from the middle portion of the formation often occurred in thin, discontinuous calcarenites located just below the Cenomanian/Turonian boundary within the *Sciponoceras gracile* Biozone. The rocks and associated fossils are similar to those at the base of the OLM, indicating regression of the sea and a recurrence of shallow-water conditions.

An extinction event occurred at or near the Cenomanian/Turonian boundary, indicated by faunal turnover in inoceramid and foraminiferan species (Kauffman 1984; Elder 1986). In South Dakota, the sharks *Carcharias saskatchewanensis* and *C. tenuiplicatus* have only been found in Cenomanian rocks. Their apparent absence in younger rocks throughout the Western Interior suggests that at least some vertebrate taxa were affected as well.

The Greenhorn Formation/Carlile Shale contact is located in the northern part of BFR, and elasmobranch fossils were collected from an interval within 0.5 m below the contact. The fossils were associated with the ammonite *Collignoniceras woollgari*, indicating an early middle Turonian age (Obradovich 1993). Species diversity is comparable to that of the basal OLM, though more than half the taxa are different (see Table 1). Rocks within this interval consist of gray calcareous shale and discontinuous calcarenites, apparently grading into non-calcareous black shale. We believe the calcarenites represent wave-influenced shoals or offshore bars related to regression of the Greenhorn Seaway during the middle Turonian (Foster 1990; VonLoh and Bell 1998). It was thought that these rocks represented transgressive lags in the basal portion of the PCM of the Carlile Shale (Cicimurri 1998), but their calcareous nature leads us to place them within the Greenhorn Formation, below non-calcareous shale of the PCM.

Uppermost Greenhorn rocks exposed at BFR are much different than those at AR. Whereas rocks in the northern Black Hills consist of calcareous shale, marl, and calcarenite, those in the southern region consist predominantly of thick limestone beds. Again, this reflects the diachronous nature of Greenhorn deposition within the Western Interior Basin. Only *Creoxyrhina mantelli*, *Squalicorax falcatus* and large teeth of *Ptychodus decurrens* have been observed in the upper Greenhorn at AR.

The selachian assemblages of the Greenhorn Formation of South Dakota are dominated by pelagic taxa (with the exception of *Rhinobatos* and possibly *Ptychodus*). The lack of benthic taxa such as sclerorhynchids and orectolobids is puzzling, especially when one considers the abundant food supply that was available (evidenced by the abundance and high diversity of teleost taxa, as well as some invertebrates). Temporally equivalent rocks of Texas and Arizona contain a variety of sclerorhynchids and orectolobids (Welton and Farish 1993; Williamson et al. 1993; Cicimurri and Bell 1996).

The majority of the taxa described in this report are rare or unknown from the Atlantic and Pacific coastal areas of North America. For example, only a single occurrence of *Ptychodus* has been documented from the Pacific Coast (Stewart 1988), and only one occurrence of *Cretoxyrhina* has been reported from the Atlantic Coast (Cappetta and Case 1975). We agree with Schwimmer (2000) that this is primarily related to a lack of temporally equivalent strata in these areas.

CONCLUSIONS

Based on ammonite occurrences, the Greenhorn Formation of South Dakota is of late middle Cenomanian to early middle Turonian age. Twenty elasmobranch taxa have been identified from vertebrate assemblages within four ammonite biozones: *Plesiacanthoceras wyomingense* (late middle Cenomanian), *Dunveganoceras pondi* (early late Cenomanian), *Scipponoceras gracile* (late late Cenomanian), and *Collignoniceras woollgari* (early middle Turonian). Though slightly older, the assemblage from the base of the formation in the southern Black Hills is identical to that from the base of the formation in the northern Black Hills. These assemblages are also very similar to temporally equivalent rocks of Kansas. Taken as a whole, the elasmobranch assemblage of the Greenhorn Fm. of South Dakota compares closely with that of the Cenomanian and Turonian of Texas.

The Greenhorn assemblage is dominated by pelagic taxa and, in North America, most of the species are known only from the Western Interior and Gulf Coast areas. *Rhinobatos* and species of *Carcharias* are found in several horizons within the Cenomanian portion of the formation, indicating that several minor regressive events took place during the transgressive phase of the Greenhorn Cyclothem.

ACKNOWLEDGEMENTS

This report stems from M.S. thesis research conducted by DJC, and guidance from committee members Gorden Bell, James Fox, James Martin, and Andrew Rogerson is greatly appreciated. We are indebted to Gorden Bell, Bill Schurmann, Dan Varner, Christian Cicimurri, Marcia Bell, and Bruce Schumacher for all of their help in the field. Barbara Beasely and Kimball Banks helped make Federal land accessible to SDSM, and Willliam Cobban confirmed the identity of the ammonites mentioned in this report. Carrie Herbel was kind enough to arrange the loan of the specimens to DJC. Gorden Bell also provided the funding for us to conduct fieldwork. Sincere thanks go to Marjorie DeCocker for drawing the teeth in Figure 7. We would also like to thank Vincent Santucci for passing the manuscript along to the reviewers. Finally, thanks to Gary Johnson, Lindsay McClelland, and Barbara Stahl. Their editorial comments improved the original version of this manuscript.

REFERENCES

Bell G.L., Jr., 1993. The First record of *Coniasaurus* (Squamata) from South Dakota. Proceedings of the South Dakota Academy of Science 72:333.

_____ and J.P. VonLoh, 1998. New Records of Turonian mosasauroids from the western United States. *In*: Martin JE, Hoganson JW and Benton RC, editors. Proceedings for the Fifth Conference on Fossil Resources; October 1998; Rapid City. Dakoterra Volume 5:15-28.

Cappetta, H., 1973. Selachians from the Carlile Shale (Turonian) of South Dakota. Journal of Paleontology 47(3):504-514.

_____, 1987. Chondrichthyes II: Mesozoic and Cenozoic Elasmobranchii. Volume 3B. Stuttgart: Gustav Fischer Verlag. 193 p.

_____ and G.R. Case, 1975. Contribution a l'etude des selaciens du groupe Monmouth (Campanien-Maestrichtien) du New Jersey. Palaeontographica 151(1-3):1-46.

_____ and _____, 1999. Additions aux faunes de selaciens du Cretace du Texas (Albien superieur-Campanien). Palaeo Ichthyologica 9:5-111.

Case, G.R., T.T. Tokaryk, and D. Baird, 1990. Selachians from the Niobrara Formation of the Upper Cretaceous (Coniacian) of Carrot River, Saskatchewan, Canada. Canadian Journal of Earth Sciences 27:1084-1094.

Cicimurri, D.J., 1998. Fossil elasmobranchs of the Cretaceous System (Neocomian-Maestrichtian), Black Hills region, South Dakota and Wyoming [M.S. Thesis]. Rapid City: South Dakota School of Mines and Technology. 197 p.

_____, 2001. Fossil selachians from the Belle Fourche Shale (Cretaceous, Cenomanian), Black Hills region of South Dakota and Wyoming. The Mountain Geologist 38(3): in press.

_____ and G.L. Bell, 1996. Vertebrate fauna of the Boquillas Formation of Brewster County, Texas: A preliminary report. Journal of Vertebrate Paleontology 16(supp. to 3):28A.

Cobban, W.A., 1951. Colorado Shale of central and northwestern Montana and equivalent rocks of the Black Hills. American Association of Petroleum Geologists 35:2170-2198.

Edwards, P., 1976. Fossil sharks (Pisces, Selachii) from the Codell Sandstone, Pueblo County, Colorado. The Mountain Geologist 13(6):67-70.

	DISTRIBUTION				
Taxon	1	2	3	4	5
Ptychodus anonymus	• •	•	•		
P. decurrens	•?	•	•	•	•
P. occidentalis	•		•		
P. whipplei	•	•	•		
Ptychodus sp.	•	•			
Squalicorax curvatus	•		•		
S. falcatus	• •	•	•		
S. volgensis	• •		•		
Scapanorhynchus raphiodon	•	•	•		
Carcharias amonensis	•?		•	•	
C. saskatchewanensis	•	•	•		
C. tenuiplicatus	•		•		
Carcharias sp.	•	•			
Johnlongia parvidens	•				
Cretodus crassidens	•	•			
C. semiplicatus	•	•	•	•	
Cretolamna appendiculata	• •	•	•	•	
Cretoxyrhina mantelli	• •	•	•	•	
Rhinobatos incertus	• •	•?	•	•?	
Cretomanta canadensis	• •	•	•		

TABLE 1. Geographic distribution of elasmobranch taxa described in this report. 1, OLM of the Greenhorn Formation, South Dakota; 2, uppermost Greenhorn Fm. of South Dakota; 3, Lincoln Limestone Member, Greenhorn Limestone of Kansas; 4, late Cenomanian-middle Turonian rocks of Texas; 5, Mancos Shale of Arizona. Occurrences for 3-5 are based on Shimada and Martin 1993, Welton and Farish 1993, Williamson et al. 1993, Cicimurri and Bell 1996, and Cappetta and Case 1999. ? indicates uncertain occurrence of the species.

EICHER, D.L., 1967. Depth of the Greenhorn sea. Paleoenvironments of the Cretaceous seaway in the Western Interior – a symposium. Colorado School of Mines, Golden. p. 145-172.

ELDER, W.P., 1986. Cenomanian-Turonian (Cretaceous) stage boundary extinctions in the Western Interior of the United States [Ph.D. dissertation]. Denver: University of Colorado. 621 p.

EVETTS, M.J., 1979. Upper Cretaceous sharks from the Black Hills region, Wyoming and South Dakota. The Mountain Geologist 16(2):59-66.

FOELL, C.J., 1982. Stratigraphy, carbonate petrography, paleontology and depositional environments of the Orman Lake Member, Greenhorn Formation (Upper Cretaceous; Cenomanian) Eastern Black Hills, South Dakota and Wyoming [M.S. thesis]. Indiana University. 172p.

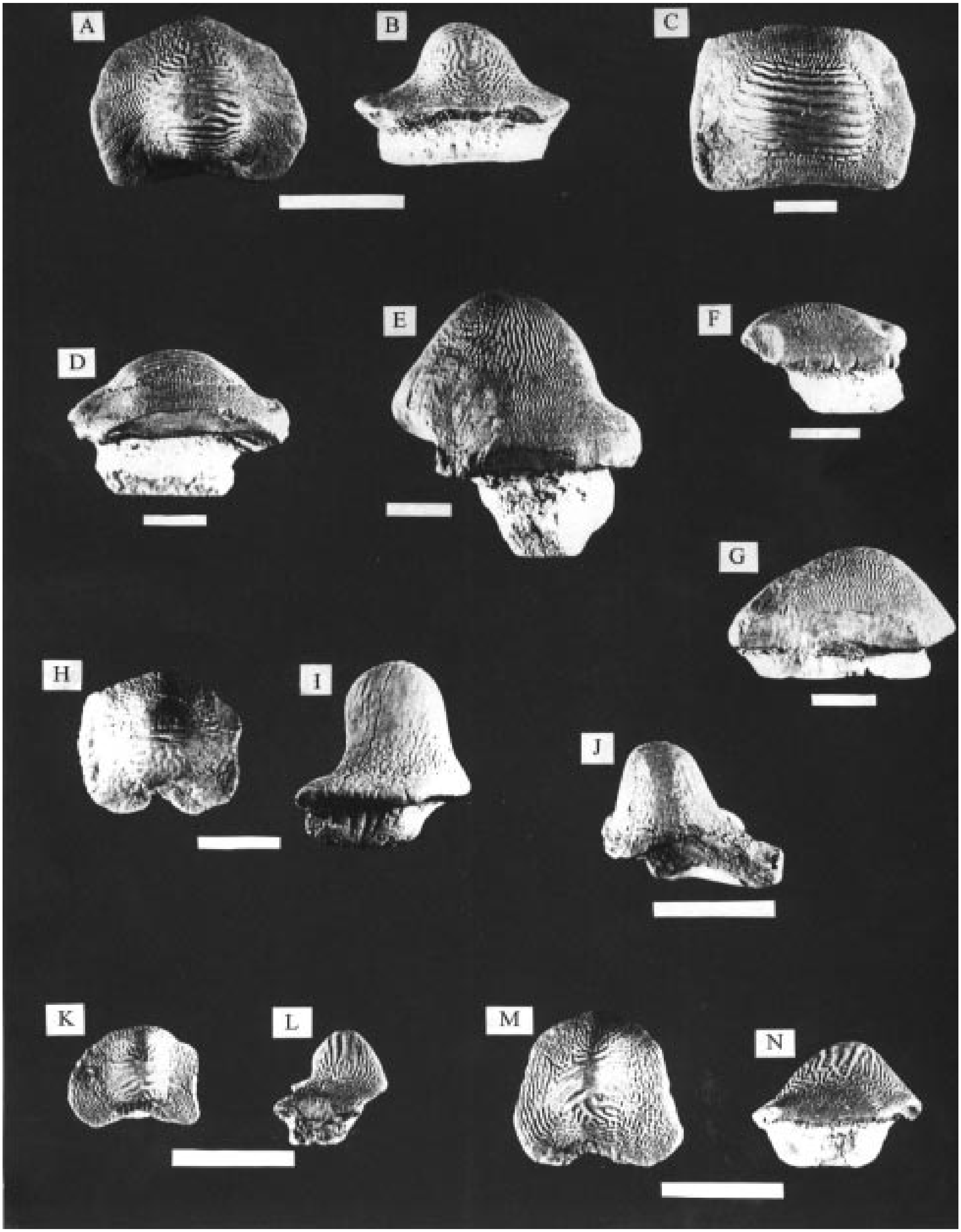


FIGURE 6. A-B, *Ptychodus anonymus*, SDSM 34923, anterior tooth; A, occlusal view, anterior at top, B, anterior view. C-D, *P. decurrens*, SDSM 34935, medial tooth; C, occlusal view, anterior at top, D, anterior view. E-G, *P. occidentalis*; E, SDSM 35233, upper medial tooth, lateral view, anterior at left; F, SDSM 35234, lower medial tooth, lateral view, anterior at left; G, SDSM 35236, lateral tooth, anterior view. H-J, *P. whipplei*, H, SDSM 3xxxx, anterior tooth, occlusal view, anterior at top, I, lateral view, anterior at right; J, SDSM 35583, lateral tooth, anterior view. K-N, *Ptychodus* sp., K, SDSM 34982, anterior tooth, occlusal view, anterior at top; L, lateral view, anterior at right; M, SDSM 34983, anterior tooth, occlusal view, anterior at top; N, lateral view, anterior at right. Scale bars = 1 cm for all specimens.

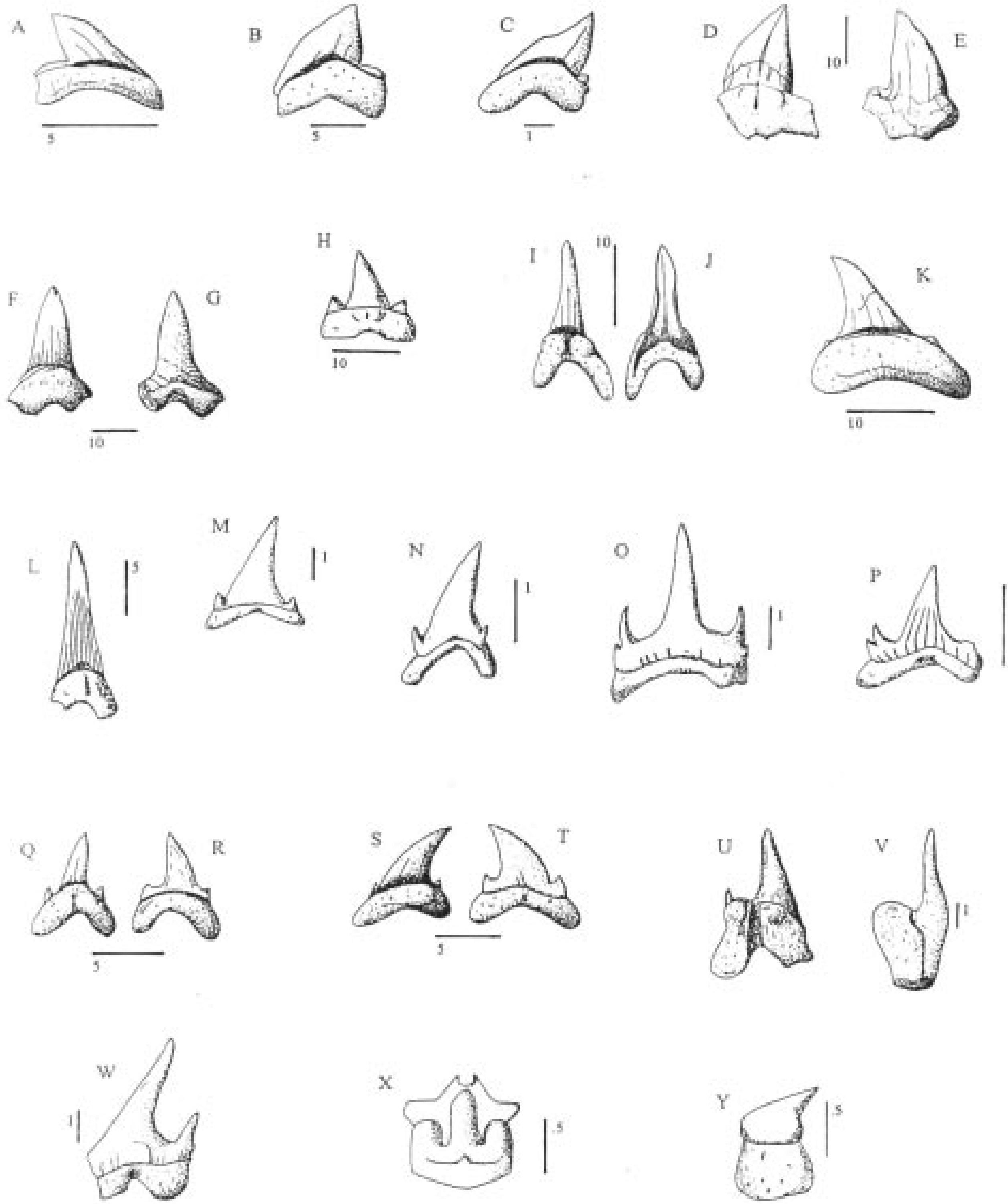


FIGURE 7. A, *Squalicorax curvatus*, SDSM 35562, anterolateral tooth, lingual view; B, *S. falcatus*, SDSM 35582, anterior tooth, lingual view; C, *S. volgensis*, SDSM 35562, anterior tooth, lingual view; D-E, *Cretodus crassidens*, SDSM 35591, anterolateral tooth, D, lingual view, E, labial view; F-G, *C. semiplicatus*, AMM 98.1.2, anterior tooth, F, lingual view, G, labial view; H, *Cretolamna appendiculata*, SDSM 35578, lateral tooth, lingual view; I-J, *Cretoxyrhina mantelli*, SDSM 35598, anterior tooth, I, lingual view, J, labial view; K, *C. mantelli*, SDSM 35599, lateral tooth, lingual view; L, *Scapanorhynchus raphiodon*, SDSM 34940, lower anterior tooth, lingual view; M, *Carcharias* aff. *C. amonensis*, SDSM 35566, anterior tooth, labial view; N, *C. saskatchewanensis*, SDSM 3555, anterior tooth, labial view; O, *C. tenuiplicatus*, SDSM 34930, anterior tooth, labial view; P, *C. tenuiplicatus*, SDSM 34920, lateral tooth, labial view; Q-T, *Carcharias* sp., SDSM 35584, Q-R, anterior tooth, Q, lingual view, R, labial view, S-T, lateral tooth, S, lingual view, T, labial view; U-V, SDSM 34979, *Johnlongia parvidens*, U, lingual view, V, mesial view; W, SDSM 34937, *J. parvidens*, lateral tooth, labial view; X, *Rhinobatos incertus*, SDSM 35640, occlusal view; Y, *Cretomanta canadensis*, SDSM 35596, lateral view. Scale bars are indicated in millimeters.

HATTIN, D.E., 1975. Stratigraphy and depositional environment of the Greenhorn Limestone (Upper Cretaceous) of Kansas. Kansas Geological Survey Bulletin 209:1-128.

KAUFFMAN, E.G., 1969. Cretaceous marine cycles of the Western Interior. The Mountain Geologist 6:227-245.

KENT, B.W., 1999. Sharks from the Fisher/Sullivan site. *In*: Weems RE, Grimsley GJ, editors, Early Eocene vertebrates and plants from the Fisher/Sullivan site (Nanjemoy Formation) Stafford County, Virginia. Virginia Division of Mineral Resources Publication 152. p. 11-37.

MACDONALD, H.R. and C.W. BYERS, 1988. Depositional history of the Greenhorn Formation (Upper Cretaceous), northwestern Black Hills. The Mountain Geologist 25:71-85.

MARTIN J.E., G.L. BELL, Jr., B.A. SCHUMACHER, and J.F. SAWYER, 1996. Geology and paleontology of the Late Cretaceous marine deposits of the southern Black Hills region. *In*: Paterson CJ, Kirchner JG, editors. Guidebook to the Geology of the Black Hills; South Dakota School of Mines Bulletin 19:51-77.

_____, B.A. SCHUMACHER, D.C. PARRIS, and B.S. GRANDSTAFF, 1998. Fossil vertebrates of the Niobrara Formation in South Dakota. *In*: Martin JE, Hoganson, JW, Benton RC, editors. Proceedings for the Fifth Conference on Fossil Resources; October 1998; Rapid City. Dakoterra Volume 5:39-54.

MEYER, R.E., 1974. Late Cretaceous elasmobranchs from the Mississippi and east Texas embayments of the Gulf coastal plain [Ph.D. Dissertation]. Texas: Southern Methodist University. 419 p.

OBRADOVICH, J.D., 1993. Cretaceous time scale. *In*: Caldwell WEG, Kauffman EG, editors. Evolution of the Western Interior Basin. Geological Association of Canada Special Paper 39. p. 379-396.

SAWYER, J.F., 1990. Depositional environment of the Turner Sandy Member of the Carlile Shale near Provo, South Dakota [M.S. Thesis]. Rapid City: South Dakota School of Mines and Technology. 224 p.

SCHWIMMER, D.R., 2000. Where are the large Late Cretaceous sharks on the Atlantic coastal plain of the USA? Journal of Vertebrate Paleontology 20(supp. to 3):68A.

SHIMADA K. and D.J. MARTIN, 1993. Upper Cretaceous selachians from the basal Greenhorn Limestone in Russell County, Kansas. Proceedings of a joint meeting of the Missouri and Kansas Academies of Science; 1993 April 23-24; Kansas City. Transactions of the Kansas Academy of Science 13:78.

SIVERSON, M., 1996. Lamniform sharks of the Mid Cretaceous Alinga Formation and Beedagong Claystone, western Australia. Paleontology 39(4):813-849.

STEWART, J.D., 1988. Paleoecology and the first North American west coast record of the shark genus *Ptychodus*. Journal of Vertebrate Paleontology 8(supp. to 3):27A.

TRICAS, T.C., K. DEACON, P. LAST, J.E. MCCOSKER, T.I. WALKER, and TAYLOR L. 1997. The Nature Company Guide to Sharks and Rays. Time Life Publishing. 288 p.

VONLOH, J.P. and G.L. BELL, Jr. 1998. Fossil reptiles from the Late Cretaceous Greenhorn Formation (Late Cenomanian-Middle Turonian) of the Black Hills Region, South Dakota. *In*: Martin JE, Hoganson JW, and Benton RC, editors. Proceedings for the Fifth Conference on Fossil Resources; October 1998; Rapid City. Dakoterra Volume 5:29-38.

WELTON, B.J. and R.F. FARISH, 1993. The collector's guide to fossil sharks and rays from the Cretaceous of Texas. Louisville: Before Time. 204 p.

WILLIAMSON, T.E., J.I. KIRKLAND and LUCAS SG., 1993. Selachians from the Greenhorn Cyclothem ("Middle" Cretaceous: Cenomanian-Turonian), Black Mesa, Arizona, and the paleogeographic distribution of Late Cretaceous selachians. Journal of Paleontology 67(3):447-474.

WILLISTON, S.W., 1900. Cretaceous fishes, selachians and pycnodonts. University Geological Survey of Kansas 6(2):237-256.

WOLBERG, D.L., 1985. Selachians from the Late Cretaceous (Turonian) Atarque Sandstone Member, Tres Hermanos Formation, Sevilleta Grant, Socorro County, New Mexico. New Mexico Geology 7(1):1-7.

AN UNUSUAL TETRAPOD TRACK MORPHOLOGY FROM THE PERMIAN COCONINO SANDSTONE, GRAND CANYON NATIONAL PARK, ARIZONA

ADRIAN P. HUNT[1] AND VINCENT L. SANTUCCI[2]
[1]Mesalands Dinosaur Museum, Mesa Technical College, 911 South Tenth Street, Tucumcari, NM 88401
[2]Fossil Butte National Monument, P. O. Box 592, Kemmerer, WY 83101

ABSTRACT—The Permian Coconino Sandstone at Grand Canyon National Park has yielded an important vertebrate ichnofauna. Currently all specimens from the Coconino Sandstone are assigned to species of *Chelichnus*. A morphologically distinct trackway has been discovered along the Hermit Trail and in Marble Canyon that differs from *Chelichnus* in: (1) possession of tail drag; (2) disparity in size between manus and pes impressions; (3) pace angulation greater than 90°; and (4) L-shaped manus impression. This represents a previously unrecognized morphology for Permian eolianites.

INTRODUCTION

Paleozoic tetrapod ichnofaunas from Grand Canyon National Park are among the most significant in North America (Hunt and Santucci, 1998a). The majority of specimens were collected by Charles Gilmore of the United States National Museum (Smithsonian) and described by him in a series of classic works (Gilmore, 1926b, 1927b, 1928a). Santucci and Wall (1995) conducted a preliminary reconnaissance of the Coconino Sandstone in the area of the Hermit Trail in Grand Canyon National Park (Fig. 1). The purpose of this paper is to describe an unusual track morphology from that location that is distinct from those previously reported within the Coconino Sandstone.

PALEOZOIC TETRAPOD TRACKS FROM THE GRAND CANYON

Schuchert (1918) is credited as the first collector of tetrapod tracks in Paleozoic strata on the South Rim of the Grand Canyon. Lull (1918) utilized the portion of the collection from the Permian Coconino Sandstone to publish the first scientific description of Paleozoic tetrapod tracks from Arizona. In 1924, the National Park Service invited Charles Gilmore to visit Schuchert's locality and to prepare an *in situ* exhibit on a now abandoned portion of the Hermit Trail (Spamer, 1984). Gilmore (1926b) described this new collection of Coconino ichnofossils and was later funded, by the Marsh Fund Committee of the National Academy of Sciences (1926) and the Grand Canyon Exhibit Committee of the National Academy of Sciences (1927), to make additional collections and exhibits (Spamer, 1984). In addition to the new trace fossil collections from the Coconino, Gilmore collected vertebrate tracks from the Hermit Shale (Permian) and Wescogame Formation of the Supai Group (Pennsylvanian). Gilmore described this new material in additional monographs (Gilmore, 1927b, 1928a) and a short paper on the first tracks from the North Rim (Gilmore and Sturdevant, 1928). Gilmore also wrote three more popular papers describing his collecting efforts in the Grand Canyon (Gilmore, 1926a, 1927a, 1928b).

For the next 70 years there was little reevaluation of Gilmore's work except by Don Baird of Princeton (Baird, 1952, Baird in Spamer, 1984). A renaissance in Paleozoic track studies took place during the mid-1990's. The Rosetta Stone for a new re-evalualtion of Permian tracks was provided by studies of the extensive ichnofaunas from the redbeds of southern New Mexico (Haubold et al., 1995a, b; Hunt et al., 1995). The New Mexico tracksites provided large sample sizes of all the most significant Permian ichnotaxa and included a broad range of preservational variants. These samples provided a new perspective on the plethora of

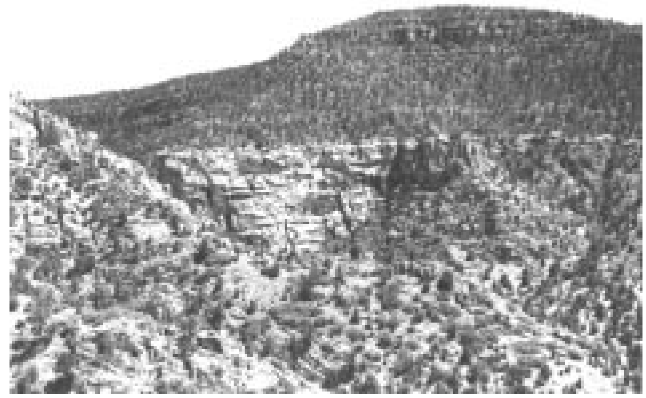


FIGURE 1. Cross section view of the Permian stratigraphy near the Hermit Trail at Grand Canyon National Park. The Coconino Sandstone is overlain by the Kaibaba Limestone.

ichnotaxonomic names of tetrapod tracks from Permian redbeds, most of which had been described on the basis of small sample sizes. During the same timeframe there was a major reevaluation of the equally confused ichnotaxonomy of tetrapod tracks from Permian eolianites (Morales and Haubold, 1995; Haubold et al., 1995a, b; McKeever and Haubold, 1996; Haubold, 1996; Hunt and Santucci, 1998a,b). Hunt and Santucci (1998a) presented a reassessment of the ichnotaxonomy of the Coconino tracks from Grand Canyon National Park on the basis of this new synthesis (Table 1).

TETRAPOD ICHNOLOGY OF THE COCONINO SANDSTONE

The first fossil footprints to be described in the scientific literature came from Permian eolianites of Scotland (Grierson, 1828). Subsequently, paleontologists described important ichnofaunas from eolian strata of Germany (Cornberger Sandstein), Colorado (Lyons Sandstone), and Arizona (Coconino Sandstone, DeChelly Sandstone), as well as additional specimens from Scotland (Hopeman, Corncockle and Locharbriggs Sandstone formations). An extensive literature describes many ichnotaxa from these formations. However, recent work spearheaded by Hartmut Haubold has demonstrated that virtually all tetrapod tracks from Permian eolianites represent three ichnospecies of one ichnogenus, with only the rarest exceptions (Haubold et al., 1995b; McKeever and Haubold, 1996; Haubold, 1996). All of the Coconino vertebrate tracks apparently fall within three species of *Chelichnus* (McKeever and Haubold, 1996). *Chelichnus* is characterized by rounded manual and pedal impressions that are of nearly equal size and that exhibit five short, rounded toe impressions (though fewer than five may be preserved). Trackways have a pace angulation of about 90°, and the manual and pedal impressions are close together (McKeever and Haubold, 1996). The three valid species of *Chelichnus* are distinguished on the basis of size alone and are presumed to be the tracks of a caseid-like animal (Haubold, 1971). *Chelichnus bucklandi* has pedal impression lengths of 10-25 mm, *C. duncani* of 25-75 mm and *C. gigas* of 75-125 mm (McKeever and Haubold, 1996). Thus, all of Gilmore's and Lull's named ichnotaxa from the Coconino Sandstone of the Grand Canyon can be placed in one of these three species. Gilmore (1927b) was aware of the similarity between some of his specimens from the Grand Canyon and those from Scotland, but he persisted with his (and Lull's) distinct ichnotaxonomy (Gilmore, 1928a).

Singularly, size is not the ideal criterion with which to distinguish between ichnospecies, however, the revised ichnotaxonomy presented here represents the current consensus (Table 1). The low ichnotaxonomic diversity of the Coconino is in keeping with the low animal diversity that would be expected in an arid dunefield.

Gilmore was aware that the Coconino Sandstone and Hermit Shale were deposited in different sedimentary environments, however, Baird (1965) was the first to emphasize that the differences between the Permian ichnofaunas of the redbeds of the American West and those of eolianites might be a result of facies differences. There has been a long tradition of recognizing ichnofacies in invertebrate traces, but the concept has only recently been applied to vertebrate tracks (Lockley et al., 1994). Tetrapod ichnofacies have been defined as "multiple ichnocoenoses that are similar in ichnotaxonomic composition and show recurrent association in particular environments (Lockley et al., 1994, p. 242). Lockley and others (1994), Hunt and others (1995), Haubold (1996) and Hunt and Lucas (1998a) have all discussed Permian tetrapod ichnofacies.

The low-diversity tetrapod ichnofauna of the Coconino Sandstone has been interpreted to represent the *Chelichnus* ichnofacies (= *Laoporus* ichnofacies of Lockley et al., 1994) that is known from the DeChelly and Coconino sandstones of Arizona, the Lyons Sandstone of Colorado, the Hopeman, Corncockle and Locharbriggs Sandstone formations of Scotland, the Cornberger Sandstein of Germany and the Los Reyunos Formation of Argentina (Hunt and Lucas, 1998a, b; Hunt and Santucci, 1998a).

UNUSUAL TRACKS

In 1993, we noted a morphologically enigmatic trackway near the present Hermit Trail and have subsequently reexamined this trackway and others in the same area. The trackway is distinct from most Coconino *Chelichnus* tracks in five characteristics (Fig. 2 and 3): (1) the trackway proceeds directly up the dune face, whereas most trackways traverse at an oblique angle; (2) the tracks are much larger than average for the Coconino; (3) there is a prominent, sinuous tail drag; (4)

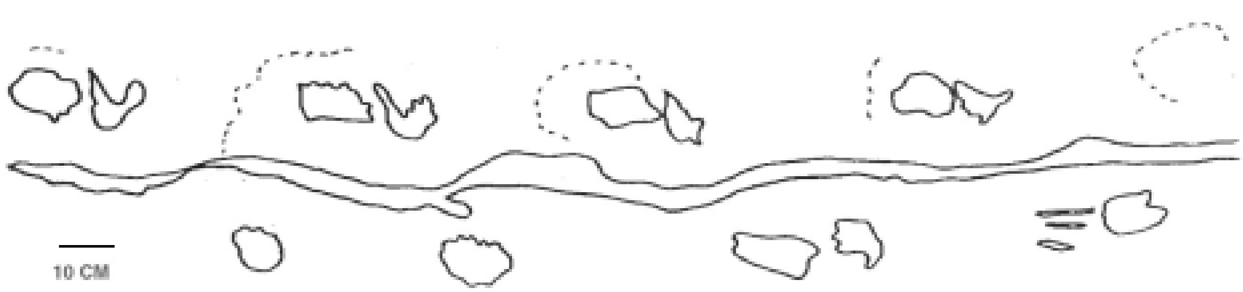


FIGURE 2. Map of trackway exhibiting unusual morphology from the Permian Coconino Sandstone near the Hermit Trail, Grand Canyon National Park, Arizona.

FIGURE 3. Overview of tracksite looking up the dune face. A small *Chelichnus duncani* trackway (left arrows) zigzags up the dune face to the right ofo the large enigmatic trackway (right arrows).

the manus print is smaller than the pes: and, (5) the manus track is L-shaped. Subsequently, a second trackway of similar morphology was discovered near the first trackway. We later noted that Price (1998, p. 21) illustrated a similar trackway from the Coconino near Buck Farm Canyon, a side canyon of Marble Canyon within Grand Canyon National Park. Price's (1998, p. 21) specimen also has a sinuous tail-drag and L-shaped manus tracks (note first manus print on the left side of trackway in foreground of photograph).

The first Hermit Trail trackway is preserved *in situ* on a bedding plane that dips 55°. The left portion of the trackway is more distinct than the right. The pes tracks are ovoid with no distinct digital impressions. The tracks are oriented with the long axis in the direction of travel. The pes tracks average 10 cm in length and exhibit a stride between 55 and 58 cm. The manus tracks average 8 cm in antero-posterior length. These tracks are variable in morphology. Several are L-shaped with one axis directed antero-lateral to the direction of travel and the other lateral to slightly postero-lateral. The tail drag is continuous and sinuous, however, it is variable in width with a maximum of 5 cm. The pace angulation varies from between 90° to 120°.

These trackways do not conform to any of the trackway morphologies described by Gilmore. Furthermore, they differ from *Chelichnus* (*sensu* McKeever and Haubold, 1995) in: (1) possession of tail drag; (2) disparity in size between manus and pes impressions; (3) pace angulation greater than 90°; and (4) L-shaped manus impression. The only other tracktypes identified in Permian eolianites are lacertoid in morphology (Haubold et al., 1995). These tracks do have larger pace angulations, disparity in size between manus and pes impressions, and tail drag marks. However, lacertoid tracks are smaller and possess small sole pads.

In conclusion, the new trackway appears to represent a new component of the Coconino ichnofauna. Further study is needed to confirm whether this represents a new ichnotaxon. It is highly unlikely, but still possible that this track morphology represents an extreme extramorphological variant of *Chelichnus*.

TABLE 1. Tetrapod ichnofauna of the Coconino Sandstone

Chelichnus duncani (Owen, 1842) (=*Baropezia arizonae, Allopus? arizonae, Baropezia eakini, Agostopus matheri, Agostopus medius, Palaeopus regularis, Barypodus tridactylus, Barypodus metszeri, Nanopus maximus, Laoporus noblei*, in part of Gilmore, 1926b)

Chelichnus gigas (Jardine, 1850) (=*Barypodus palmatus, Amblyopus pachypodus, Baropus cocninoensis*)

Chelichnus bucklandi (Jardine, 1850) (=*Dolichopodus tetradactylus, Laoporus schucherti, Laoporus coloradensis, Nanopus merriami, Laoporus noblei*, of Lull, 1918)

ACKOWLEDGEMENTS

We thank Terrell Jones, Masaki Matsukawa, Luke Santucci and Bill Wall for assistance with fieldwork. We also extend our appreciation to John Foster, Spencer Lucas, Lindsay McClelland, and Deb Mickelson for reviewing the draft version of this manuscript.

REFERENCES

BAIRD, D., 1952. Revision of the Pennsylvanian and Permian footprints *Limnopus*, *Allopus* and *Baropus*: Journal of Paleontology, v. 26, p. 832-840.

_____, 1965. Footprints from the Cutler Formation: United States Geological Survey Professional Paper 503C, p. C47-C50.

GILMORE, C.W., 1926a. Collecting fossil footprints in Arizona: Smithsonian Miscellaneous Collections, v. 78(1), 20-23.

_____, 1926b. Fossil footprints from the Grand Canyon: Smithsonian Miscellaneous Collections, v. 77(9), 41 p.

_____, 1927a. Collecting fossil footprints in the Grand Canyon, Arizona: Smithsonian Miscellaneous Collections, v. 78(7), 45-48 p.

_____, 1927b. Fossil footprints from the Grand Canyon: second contribution: Smithsonian Miscellaneous Collections, v. 80(3), 78 p.

_____, 1928a. Fossil footprints from the Grand Canyon: third contribution: Smithsonian Miscellaneous Collections, v. 80(8), 16 p.

_____, 1928b. Fossil footprints in the Grand Canyon of the Colorado, Arizona: *in* Explorations and fieldwork of the Smithsonian Institution 1927, Smithsonian Institution Publication 2957, p. 7-10.

_____ and G.E. STURDEVANT, 1928. Discovery of fossil tracks on the north rim of the Grand Canyon: Science, v. 67, p. 216.

GRIERSON, J., 1828. On footsteps before the flood, in a specimen of red sandstone: Edinburgh Journal of Science, v. 8, p. 130-134.

HAUBOLD, H., 1971. Ichnia amphibiorum et reptiliorum fossilium: Handbuch der Paleoherpetologie, Teil 18: 1995.

Stuttgart, Gustav Fischer Verlag, 124 p.

_____, 1996. Ichnotaxonomie und Klassifikation von Tetrapodenfaehrten aus dem Perm: Hallesches Jahrbuch Geowissenschaften, v. B18, p. 23-88.

_____, A.P. Hunt, S.G. Lucas, and M.G. Lockley, 1995a. Wolfcampian (Early Permian) vertebrate tracks from Arizona and New Mexico: New Mexico Museum of Natural History and Science Bulletin, v. 6, p. 135-165.

_____, M.G. Lockley, A.P. Hunt, and S.G. Lucas, 1995b. Lacertoid footprints from Permian dune sandstones, Cornberg and DeChelly sandstones: New Mexico Museum of Natural History and Science Bulletin, v. 6, p. 235-244.

Hunt, A.P. and S.G. Lucas, 1998a. Implications of the cosmopolitanism of Permian tetrapod ichnofaunas: New Mexico Museum of Natural History and Science Bulletin, v. 12, p. 55-57.

_____ and _____, 1998b. Vertebrate ichnofaunas of New Mexico and their bearing on Early Permian tetrapod ichnofacies:New Mexico Museum of Natural History and Science Bulletin, v. 12, p. 63-65.

_____ and V.L. Santucci, 1998a. Taxonomy and ichnofacies of Permian tracks from Grand Canyon National Park, Arizona; *in* Santucci, V. L. and McClelland, L., (eds.), National Park Service Paleontological Research: United States Department of the Interior, National Park Service, Geologic Resources Division Technical Report NPS/NRGRD/GRDTR-98/01, p. 94-96.

_____ and _____, 1998b. An identification key to Permian tetrapod tracks from Grand Canyon National Park; *in* Santucci, V. L. and McClelland, L., (eds.), National Park Service Paleontological Research: United States Department of the Interior, National Park Service, Geologic Resources Division Technical Report NPS/NRGRD/GRDTR-98/01, p. 97-98.

_____, S.G. Lucas, M.G. Lockley, H. Haubold, and S. Braddy, Tetrapod ichnofacies in Early Permian red beds of the American Southwest: New Mexico Museum of Natural History and Science Bulletin, v. 6, p. 295-301.

Lockley, M.G., A.P. Hunt, and C. Meyer, 1994. Vertebrate tracks and the ichnofacies concept: implications for paleoecology and palichnostratigraphy; *in* Donovan, S., (ed.), The paleobiology of trace fossils: John Wiley, London, p. 241-268.

Lull, R.S., 1918. Fossil footprints from the Grand Canyon of the Colorado: American Journal of Science, fourth series, v. 45, p. 337-346.

McKeever, P.J. and H. Haubold, 1996. Reclassification of vertebrate trackways from the Permian of Scotland and related forms from Arizona and Germany: Journal of Paleontology, v. 70, p. 1011-1022.

Morales, M. and H. Haubold, 1995. Tetrapod tracks from the Lower Permian DeChelly Sandstone of Arizona: systematic description: New Mexico Museum of Natural History and Science Bulletin, v. 6, p. 251-261.

Price, L.G., 1998. Grand Canyon: the story behind the scenery: Las Vegas, KC Publications, 64 p.

Santucci, V.L. and W.P. Wall, 1995. Climbing up sand dunes in the Permian: New tracksites from Grand Canyon National Park, Arizona. *in* Santucci, V. L. and McClelland, L., (eds.), National Park Service Paleontological Research: United States Department of the Interior, National Park Service, Technical Report NPS/NRPO/NRTR-95/16, p. 64-65.

Schuchert, C., 1918. On the Carboniferous of the Grand Canyon of Arizona: American Journal of Science, fourth series, v. 45, p. 362-369.

Spamer, E. E., 1984. Paleontology in the Grand Canyon of Arizona: 125 years of lessons and enigmas from the late Precambrian to the present: The Mosasaur, v. 2, p. 45-128.

DINOSAUR TRACKWAY FROM THE FERRON SANDSTONE MEMBER OF THE MANCOS SHALE FORMATION (UPPER CRETACEOUS) OF CENTRAL UTAH

RAMAL JONES
Radiological Health Department, University of Utah, Salt Lake City, UT 84112

ABSTRACT— To date, our knowledge of the large terrestrial vertebrae faunas on the western shore line of the Cretaceous sea way in Central Utah, from the Middle Cretaceous Albian period to the Upper Cretaceous Campanian period, remains sparse. This is due in part to taphonomic bias (lack of preservation), as well as the paucity of exposed strata. The result is large gaps, in the faunal record, notable in the large vertebrae faunal record. An example is the Ferron Sandstone Member of the Mancos Shale Formation, Eastern-Central Utah. The Ferron Sandstone Member is a thin strip of exposed coastal plain on the western shore of the Cretaceous sea. The Ferron Sandstone Member is Middle to Upper Turonian age (Franczyk 1991) and not noted for vertebrae fossils or track. The Upper Turonian age is a mid point in the dinosaur faunal gap between the Middle Cretaceous Albian period and the Upper Cretaceous Campanian period. The Moore Trackway (described herein) represents an ornithopod dinosaur that walk the coastal plain approximately ninety million years ago. The location of the trackway exposes it to a high probability of vandalism.

INTRODUCTION

The Ferron Sandstone Member of the Mancos Shale Formation of Eastern Utah, a coastal plain environ ment, is not noted for vertebrae fossil bone or tracks. While other late Cretaceous coastal plain environments such as the later Upper Cretaceous (Campanian) Blackhawk Formation (Doelling, 1972) from the Mesaverde Group and the earlier, Lower Cretaceous (Albian) Dakota Sandstone Formation, do not contain fossilized bone. But do contain an abundant of vertebrae tracks. Most of the tracks in the Dakota Sandstone Formation are found in Colorado along what was once the eastern shore line of the Cretaceous Sea. While there is an abundance of tracks in the Dakota Sandstone in Colorado, the Dakota Sandstone Formation along the western shore line of the Cretaceous Sea contains very few tracks.

The tracks in the Dakota Sandstone (Lockley and Hunt, 1995) and the Blackhawk Formation (Parker and Rowley, 1989) give paleontologists an understanding of the large terrestrial vertebrae faunas that inhabited the eastern shore line of the Cretaceous Sea during the Middle Cretaceous (Albian) and the western shore line during the Upper Cretaceous (Campanian). Understanding of the large terrestrial vertebrae faunas on the western shore line from the late Middle Cretaceous (Albian) to the late Upper Cretaceous (Campanian) is as yet poorly documented. Tracks in the Ferron Sandstone during the Middle to Upper Turonian in Utah are rare.

This purpose of this paper is to report on a vertebrate trackway of late Cretaceous age, in the Ferron Sandstone Member of the Mancos Shale Formation (Middle to Upper Turonian) (Hintze, 1982). A picture and caption of this trackway are briefly mentioned in DeCourten (1998).

The trackway was shown to the author in 1998 by Jim Nielsen from Castle Dale, Utah. The trackway is located along side of a graveled road. This road runs between the almost ghost town of Moore and Interstate highway I-70 in Emery County, Utah. Hereafter, the site is refer to as the Moore Tracksite.

STRATIGRAPHIC CONTEXT

The Ferron Sandstone Member, a delta /coastal plain environment, is a regressional sequence of the Great Western Interior Seaway sometimes is referred to as the Cretaceous Seaway (Ryer, 1991). The age of the Ferron Sandstone Member of the Mancos Shale Formation is Late Cretaceous (Middle to Upper Turonian) (Hintze, 1982).

The Ferron Sandstone Member on the western side of the San Rafael anticline dips to the west with a North-South strike. Thus, the Ferron Sandstone forms an erosion resistant escarpment that is exposed for long periods of time, allowing for the formation of what is referred to as desert varnish. Desert varnish consists of a blue-black veneer of iron and manganese oxides that commonly forms on exposed sandstone in arid climates.

The trackway runs across the top of a 10 X 5 meter wide and 2.5 meter thick block of sandstone. It appears that the block has fallen from the Ferron Sandstone escarpment located directly to the north of the trackway. The top of the block has a coating of desert varnish, indicating that the trackway had been exposed to the environment for a long period. The desert varnish and the thickness of the block provide evidence that this block of sandstone came from the very top of the Ferron Sandstone escarpment, which was the last oscillating sequence in the disposition of the Ferron Sandstone Member of the Mancos Shale Formation (Ryer, 1991). The top of the Ferron Sandstone Member is Upper Turonian age, which is approximately 90 million years old. Therefore the Moore Trackway (Fig. 1) is very likely of Upper Turonian age.

MORPHOLOGY OF TRACKS

Vertebrate tracks are preserved as: 1- natural casts, made by the infilling of sediments after the print was made, 2- original prints or tracks, and 3- undertracks, made by the pressure of the original impression being transmitted to an underlayer beneath the original sedimentary layer (Lockley and Hunt, 1995). The Moore Trackway consists of original prints or tracks and natural casts.

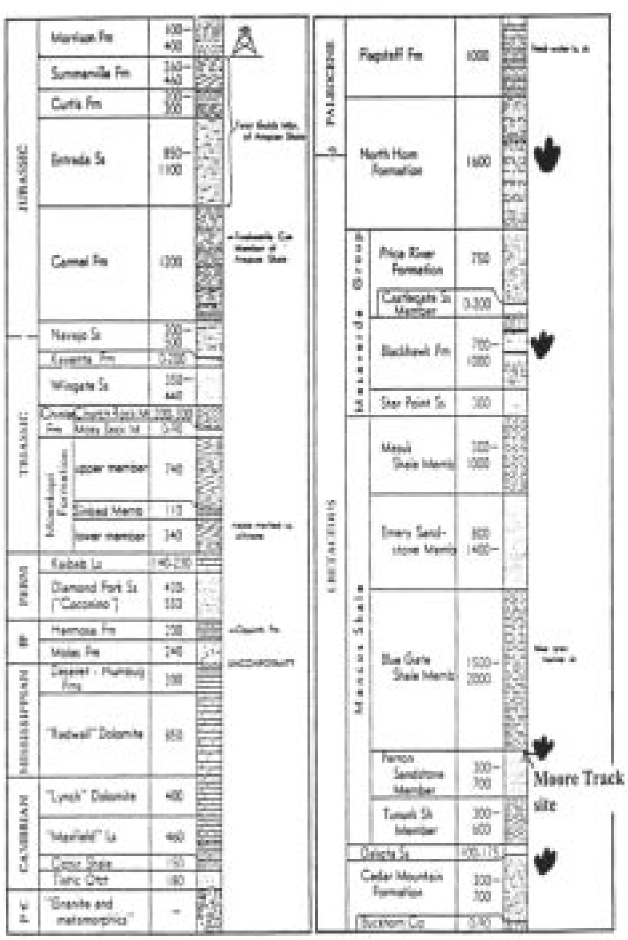


FIGURE 1. The stratigraphic position of the Moore Track site in the Ferron Sandstone Member of the Mancos Shale Formation of Eastern Utah, (Hintze, 1982).

THE MORPHOLOGY OF THE MOORE TRACKWAY

The trackway (Fig. 2) consists of nine tridactyl foot prints, five of the left pace and four of the right pace made by a single animal. There is no evidence of fore, prints which indicate that the animal was bipedal. The tracks are not well defined. The only character that is consistently defined (in three of the tracks) is the toe print on the medial side on the left pace. The lengths for tracks number 1, 3 and 7 varied from 18cm to 40cm. This variation in the track's length is due to the fact that the posterior edge of the tracks are not well defined. This variation could also be due to metatarsal impressions or heel scrapes which tends to elongate the track (Lockley and Hunt, 1995).

The track widths varied from 18cm to 27cm, once again, the lateral edges of the tracks are not well defined, causing the widths of the tracks to vary. Some of the tracks as viewed laterally are domed-shaped, with the thickest section of the dome at the posterior edge. The thickness decreases as the anterior end of the track is approach.

The footfalls in the Moore Trackway show a consistent 97cm length in the left and right paces. The widths between the left paces and right paces are a consistent 16 cm. The width between the tracks, is so narrow that the medial edge of the prints are close to or touching the mid line of the trackway.

DISCUSSION

It is unlikely that we will be able to identify with certainty the maker of the Moore Trackway. The identification of the vertebrate trackmaker is problematic because only exceptionally well preserved tracks can be used identify taxa and even these identifications are uncertain unless the fossilized bones of the animal are found in the same strata, even then it is difficult to be confident. The preservation of foot prints in the Moore Trackway is insufficient to identify the taxa below the level of or that there will not be any attempt the identify the animal below the level of ornithopod.

There are some characters that the tracks do reveal about this animal. The prints show the 2nd and 3rd digit indicating that animal was tridactyl. The major differences between ornithopod tracks and theropod tracks, is that the theropod track has claw impressions (yet claws impressions do not always show up in mud) and the ornithopod track has a more square heel or metatarsal impressions. The Moore Trackway prints show no claw impressions and the posterior edge is square or blunt shape. These characters suggest that the track maker was an ornithopod dinosaur (Gillette and Lockely, 1989).

The trackway width is narrow, suggesting that the animal walked with an upright stance as dinosaurs do rather than the reptilian sprawling stance (Wade, 1989). The footfalls in the Moore Trackway show a consistent 97cm length in the left and right paces. This consistency in the sequences of footfalls in the track-way implies that the trackmaker used a regular or symmetrical gait and was probability walking rather than running. Trackway evidence suggests that dinosaurs, like other vertebrates, typically moved at slow speeds (Thulborn, 1982).

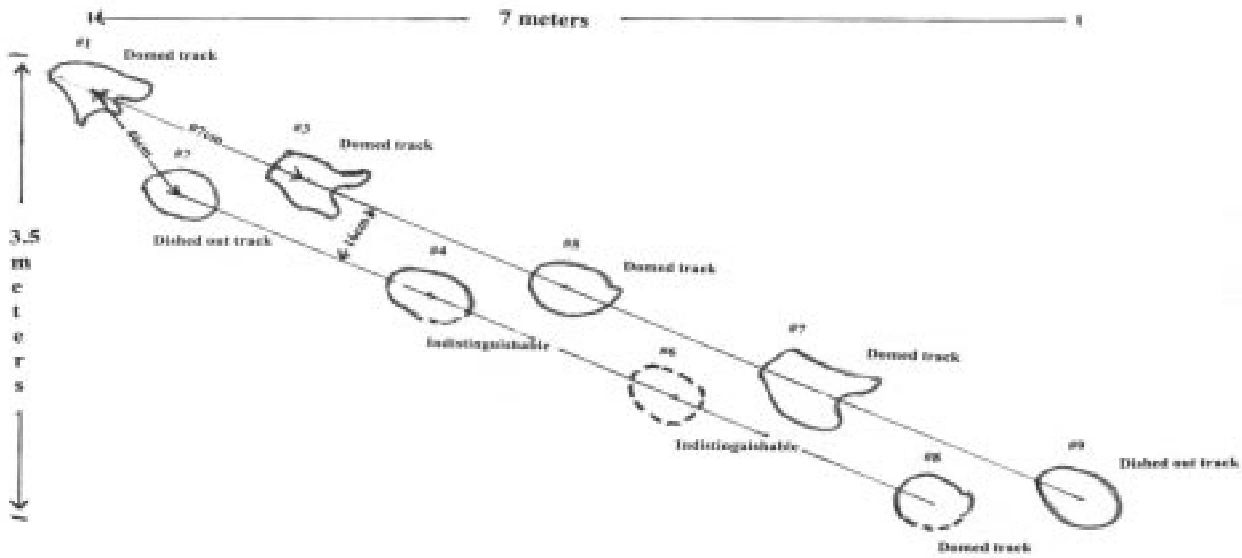


FIGURE 2. The Moore Trackway in the Ferron Sandstone Member of the Mancos Shale Formation of Eastern Utah.

The hip height of the animal can be estimated multiplying the length of the print by 4 (Alexander, 1976) for a small ornithopod and by 5.9 for a large ornithopod. The print length for the Moore Trackway assuming no heel scrape is 18 cm and assuming it is a small ornithopod, an estimate of hip height for the animal would be 4 X 18 cm = 72 cm. The 3rd digit is slightly off set laterally from the pace center line indicating that the animal's feet rotate inward slightly as the animal is walking. This is a character of ornithopod.

Age		M-yrs	Stratigraphic Unit
Late Cretaceous	Maastrichtian	65 to 74.5	
	Campanian	74.5 to 84	Blackhawk Formation 14 morphotypes
	Santonian	84 to 87.5	
Middle Cretaceous	Coniacian	86.3 to 88.7	
	Turonian	88.7 to 93.3	Mancos Shale Formation, Ferron Sandstone Member
	Cenomanian	93.3 to 97.5	
	Albian	97.5 to 113	Dakota Sandstone Formation
Lower Cretaceous	Aptian	113 to 119	
	Neocomian	119 to 144	

FIGURE 3. Comparative stratigraphy of vertebrate track-bearing Cretaceous rocks deposited along the western shore line of the Cretaceous Sea in central Utah.

SUMMARY

The Upper Turonian age of the Moore Trackway is what makes this trackway important. The Upper Turonian age is a mid point in the dinosaur faunal gap between the Middle Cretaceous Albian period and the Upper Cretaceous Campanian period (Fig. 3). The Moore Trackway basically says that an animal walked this coastal plain ninety million years ago, and that animal was more than likely a ornithopod dinosaur. This adds one more piece to puzzle of the large terrestrial vertebrae faunal along the western shore of the Cretaceous Sea Way during the Upper Turonian age .

ACKNOWLEDGMENTS

Scott D. Sampson Ph.D., for reviewing this paper. Bill and Judy Peterson, for track site measurements and documentation. Dr. Lehi F. Hintze, for permission to use the stratigraphic column in Figure 1.

REFERENCES

ALEXANDER, R.M., 1976. Estimates of speeds of dinosaurs. Nature 261: 129-130.

DECOURTEN, F., 1998. Dinosaurs of Utah, University of Utah Press, Salt Lake City, Utah. pp 213.

FRANCZYK, K.J. and J.K. PITMAN, 1991. Latest Cretaceous Nonmarine Depositional system In The Wasatch Plateau Area: Reflections Of Foreland To Intermontane Basin Transition, Geology of Eastern-Central Utah, Utah Geological Association Publication 19, pp 79.

GILLETTE, D.D. and M.G. LOCKELY, 1989. Dinosaur Tracks and Traces, Cambridge University Press, New York, N. Y. pp 442.

HINTZE, L.F., 1982. Geologic History of Utah, BYU Geology Studies, Vol. 20, Pt. 3. pp 70 fig.46; p. 143, chart 25.

LOCKLEY, M.G. and A.P. HUNT, 1995. Dinosaur Tracks, Columbia University Press, New York, NY. pp 1-30,192-212.

Parker, L.R. and R.L. Rowley, 1989. Dinosaur Footprints from a Coal Mine in East-Central Utah, Dinosaur Tracks and Traces, Cambridge University Press, New York, NY pp 362.

Ryer, T.A., 1991. Stratigraphy, Facies, And Depositional History of the Ferron Sandstone in the Canyon of Muddy Creek, East-Central Utah, Geology of Eastern-Central Utah, Utah Geological Association Publication 19, pp 45.

Thulborn, R.A., 1982. Speed and Gaits of Dinosaurs, Paleogeography, Palaeoclimatology, Palaeoecology, 38, 227-56.

Wade, M., 1989. The Stance of Dinosaur and the Cossack Dancer Syndrome. Dinosaur Tracks and Traces, Cambridge University Press, New York, N. Y. pp73.

RESTORATION OF LATE TRIASSIC LANDSCAPES AT THE PETRIFIED FOREST NATIONAL PARK, ARIZONA

SPENCER G. LUCAS
New Mexico Museum of Natural History, 1801 Mountain Road NW, Albuquerque, NM 87104

ABSTRACT— Using the wealth of research data on the stratigraphy, sedimentology and paleontology of the Upper Triassic strata exposed at Petrified Forest National Park, Arizona, artist Mary Sundstrom undertook three landscape restorations of the Park during the Late Triassic, representing approximately 225, 220 and 215 million years ago. They are intended to be used in exhibition and other interpretive information for visitors to the Park.

INTRODUCTION

Upper Triassic rocks exposed in Petrified Forest National Park (PEFO) preserve a record of riverine, channel and floodplain environments and the extinct biotas that inhabited them between approximately 225 and 215 million years ago. For decades, scientific researchers have studied the diverse aspects of the geology and paleontology of the Upper Triassic strata exposed at PEFO. It is thus possible to reconstruct with some accuracy the depositional environments and biota of PEFO during 15 million years of Late Triassic history. To do so, artist Mary Sundstrom, under my direction, drew three restorations, each corresponding to a time slice during this 15 million-year-long history. This article presents those drawings and briefly reviews their basis.

THE DRAWINGS

The three drawings (Figs. 1-3) are full-color restorations executed as hand-drawn originals that are now at PEFO. The drawings show the restored landscape, and, in cross section, the buried layers of Upper Triassic sediment (scaled to actual thicknesses). Each drawing thus is a cut-away, three-dimensional figure. The stratigraphic perspective of the drawings is cumulative, so that the Painted Desert cross section (Fig. 3) encompasses the entire section of rock deposited at the PEFO during the interval 215-225 million years ago.

TEEPEES TIME

The oldest Triassic rocks exposed at PEFO are color-banded (gray, purple, blue and red) mudstones and thin lenses of gray and tan sandstone. These strata are approximately 225 million years old and are best exposed at the Teepees area in the southern part of PEFO (Lucas, 1993; Heckert and Lucas, 1995b). These rocks represent part of a vast, muddy tropical floodplain (Fig. 1) (e.g., Dubiel, 1989). Small rivers meandered across this landscape, heading northwestward to a seashore that lay near the present Utah-Nevada border. Large plant eaters, such as the cow-sized mammal-like reptile *Placerias*, browsed along the river banks.

BLUE MESA TIME

About 220 million years ago, when the rocks that cap Blue Mesa (Sonsela Sandstone) in the southern part of the PEFO were deposited, the muddy floodplain was replaced by a wide braidplain crisscrossed by large, gravelly-bedded rivers (Fig. 2) (e.g., Dubiel, 1989). This change probably was due to a slowing of the rate at which the crust was subsiding in western North America during the Late Triassic (Blakey and Gubitosa, 1984). Large trees grew along the river courses, and their fossilized stumps and logs became the Park's famous petrified forests (Heckert and Lucas, 1995a). Plant-eating reptiles, such as the heavily armored *Desmatosuchus*, foraged on the forest floors.

PAINTED DESERT TIME

About 215 million years ago, when the red-bed mudstones and sandstones in the Painted Desert formed, the Triassic river system had again changed. Now, it was again a vast muddy floodplain (E.g., Dubiel, 1989). But, unlike Teepees time, some 10 million years earlier, huge rivers meandered across this floodplain, and tall trees lined the watercourses (Fig. 3). These trees became the logs of the Black Forest seen near Kachina Point. Crocodile-like phytosaurs, some as much as 7 meters long, hunted along the river banks.

CONCLUSION

The drawings of restored Late Triassic landscapes in PEFO depict three times during the evolution of the Late Triassic river system and biota. They are intended to be used in exhibition and other interpretive information for visitors to PEFO.

ACKNOWLEDGMENTS

PEFO financially supported the production of the drawings. Mary Sundstrom executed the artwork, and Daniel Weismann provided computer support. Three anonymous reviewers provided helpful comments on an earlier version of the manuscript.

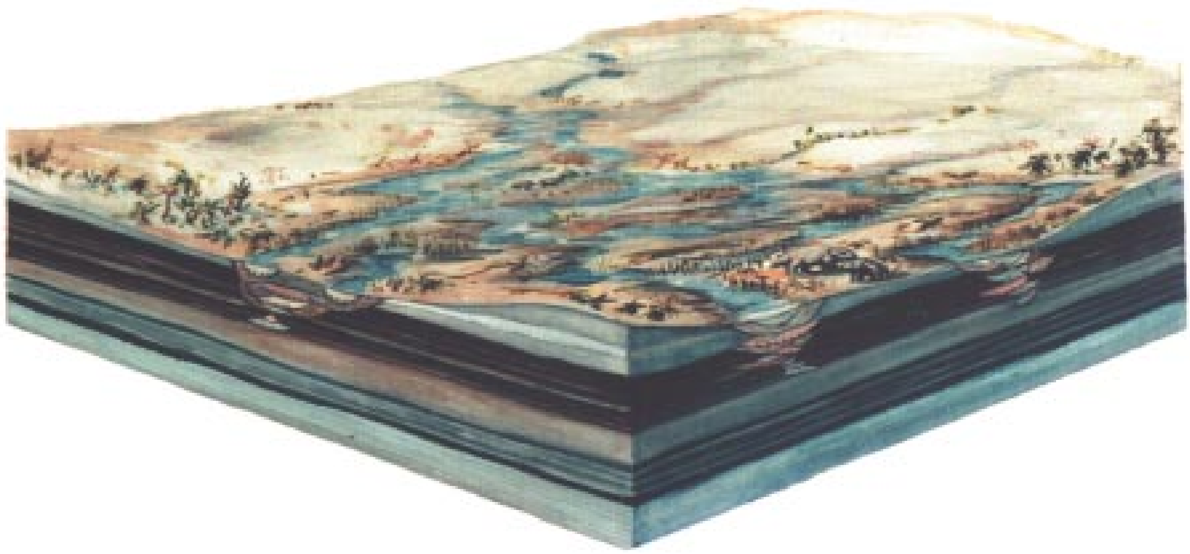


FIGURE 1. Restoration of the Late Triassic landscape at Petrified Forest National Park during “Teepees Time,” about 225 million years ago.

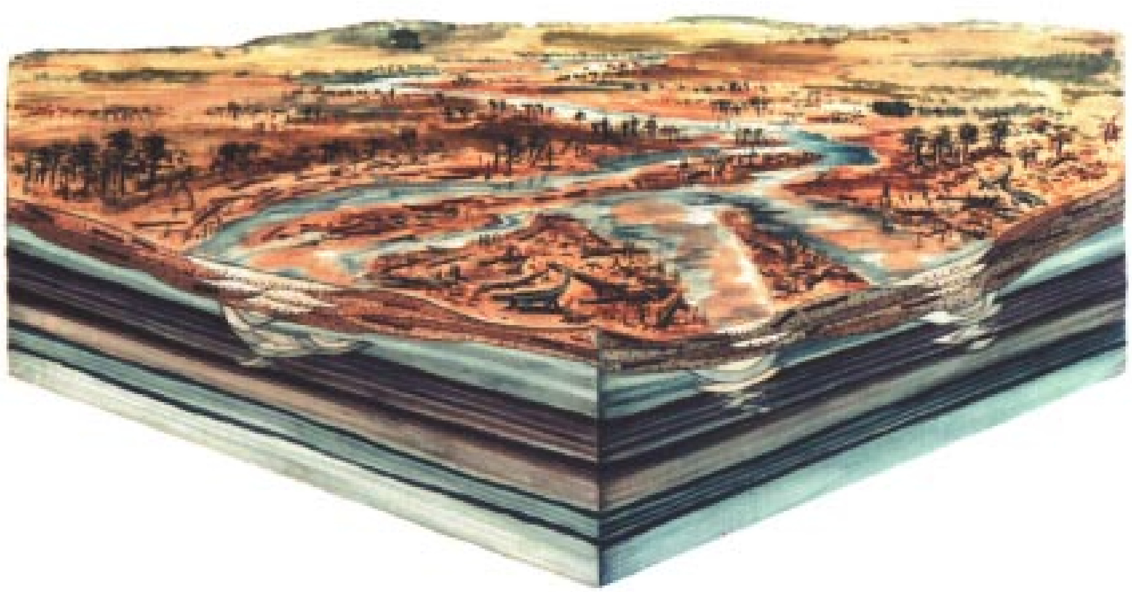


FIGURE 2. Restoration of the Late Triassic landscape at Petrified Forest National Park during “Blue Mesa Time,” about 220 million years ago.

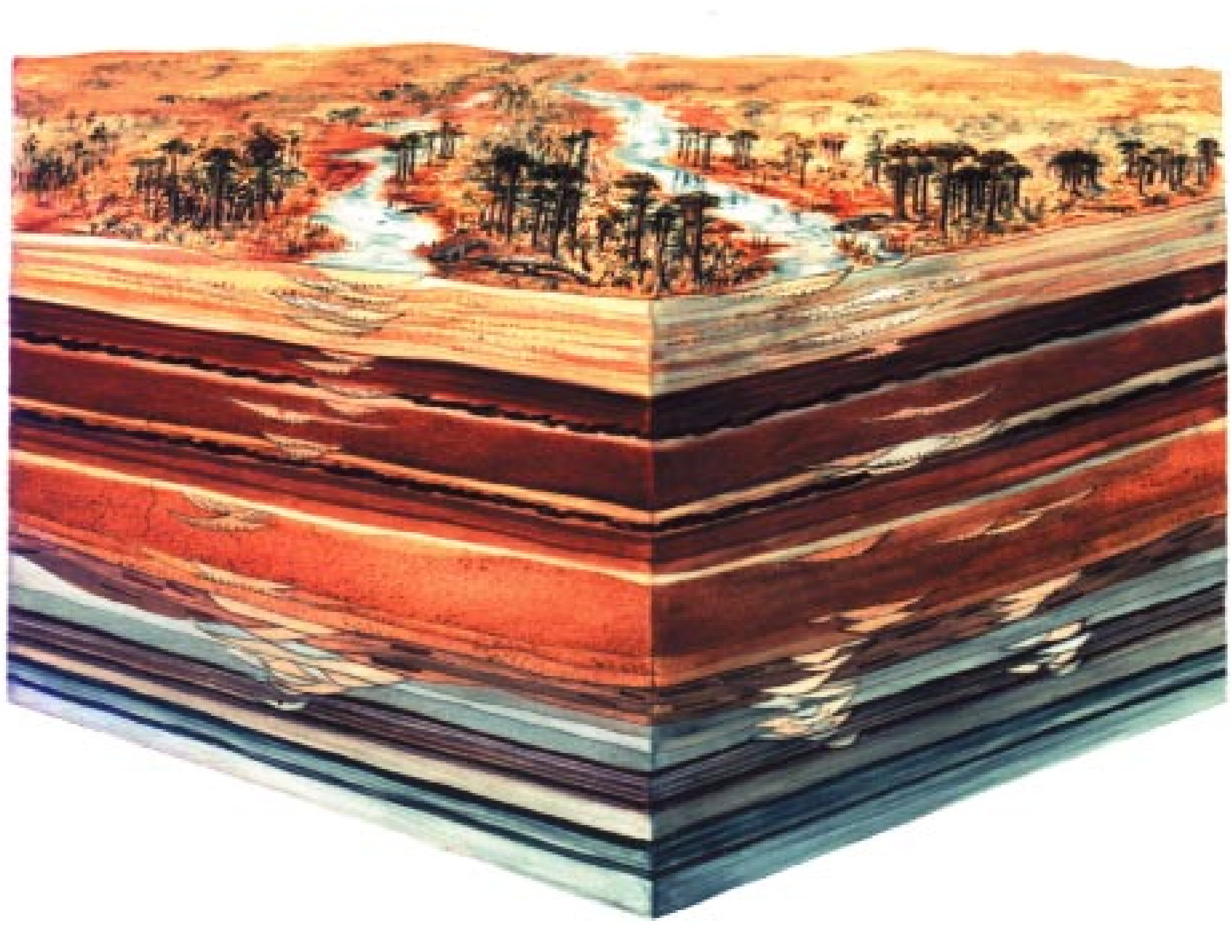


FIGURE 3. Restoration of the Late Triassic landscape at Petrified Forest National Park during "Painted Desert Time," about 215 million years ago.

REFERENCES

BLAKEY, R.C., AND R. GUBITOSA, 1984. Controls on sandstone body geometry and architecture in the Chinle Formation (Upper Triassic), Colorado Plateau. Sedimentary Geology, 38: 51-86.

DUBIEL, R.F., 1989. Depositional and climatic setting of the Upper Triassic Chinle Formation, Colorado Plateau, in Lucas, S. G., and Hunt, A. P., eds., Dawn of the age of dinosaurs in the American Southwest: Albuquerque, New Mexico Museum of Natural History, p. 171-187.

HECKERT, A.B., AND LUCAS, S.G., 1995a. Stratigraphic distribution and age of petrified wood in Petrified Forest National Park, Arizona, in Santucci, V. L., and McClelland, L., eds., National Park paleontological research: Geologic Resources Division Technical Report NPS/NRGRD/GRDTR-98/01, p. 125-129.

______, AND ______, 1995b. The oldest Triassic strata exposed in the Petrified Forest National Park, Arizona, in Santucci, V. L., and McClelland, L., eds., National Park paleontological research: Geologic Resources Division Technical Report NPS/NRGRD/GRDTR-98/01, p. 129-134.

LUCAS, S.G., 1993. The Chinle Group: Revised stratigraphy and biochronology of Upper Triassic nonmarine strata in the western United States. Museum of Northern Arizona Bulletin, 59:27-50.

THE FISH CREEK CANYON ICHNOFAUNA: A PLIOCENE (BLANCAN) VERTEBRATE FOOTPRINT ASSEMBLAGE FROM ANZA-BORREGO DESERT STATE PARK, CALIFORNIA

PAUL REMEIKA
Anza-Borrego Desert State Park, 200 Palm Canyon Drive, Borrego Springs, CA, 92004

ABSTRACT— An ubiquitous avian and mammaloid hoof- and footprint vertebrate ichnofauna is identified from basin-margin sediments in the Vallecito-Fish Creek Basin of Anza-Borrego Desert State Park, California. The terrestrial assemblage is one of the most varied yet discovered from late Pliocene (Blancan) deposits. Seven morphofamilies are recognized, represented by nine ichnospecies with morphologic parameters quantified. Four new ichnospecies are herein proposed. The ichnofauna includes *Gruipeda diabloensis*, a small ansiodactyl bird; *Mustelidichnum vallecitoensis* (new), an aquatic musteloid; *Chelipus therates*, a typical carnivorian canoid; *Pumaeichnum milleri*, an intermediate feloid; *P. stouti* (new), a large feloid; *Hippipeda downsi*, a monodactyl equoid; *Lamaichnum borregoensis*, a small llamoid; *Megalamaichnum albus* (new), a large llamoid; and *Stegomastodonichnum garbanii* (new), a probable gomphotherioid. Most mammaloid trackmakers are hitherto unknown from the fossil record of the study area but do occur within the known osteological record of the stratigraphically younger Vallecito Badlands.

Footprints are preserved as positive ceiling casts on the undersides of thick, overhanging sandstone ledges, or as natural negative floor impressions associated with various interstratified, dessication mud drapes. Well-documented tracksites occur throughout multiple stratigraphic levels of a vertical-continuous mixed-affinity marine-deltaic (Yuha Formation), delta-plain (Palm Spring Formation), and fluvial-alluvial fan (Ocotillo Formation) transition zone exposed between Hanging Tracks Wash in the Fish Creek Badlands (Blancan II), and Arroyo Tapiado in the Vallecito Badlands (Blancan IV-V). The majority of tracksites occur below and above Fish Creek Canyon (Blancan III). This report provides a significant treatise on identification for, and expansion of, the morphological ranges known among Neogene vertebrate ichnotracks of western North America.

INTRODUCTION

The Neogene basin-margin sedimentary fill of the structurally-depressed Vallecito-Fish Creek Basin half-graben was deposited under terrestrial conditions in response to the kinematics of lithospheric extension (Remeika, 1995, 1997). Such high energy environments typically are poorly fossiliferous in terms of a vertebrate body-fossil record. Although microvertebrate material of the Arroyo Seco Local Fauna (Downs and White, 1968; Cunningham, 1984; White et al., 1991) and a significant silicified wood paleoflora (Remeika et al., 1988; Remeika, 1994) is documented from these deposits, the most spectacular fossil resource is its vertebrate ichnofauna, yielding a surprisingly good census of bird, musteloid, canoid, feloid, equoid, llamoid, and gompotherioid. Given the restricted nature of other fossils, the stratigraphic abundance of tracks warrants greater attention as a significant component of paleontologic research, contributing to our understanding of the temporal, spatial distribution, and paleoecology of the Fish Creek Canyon Ichnofauna (Remeika, 1999) during the Pliocene Epoch.

Altogether, nine vertebrate ichnospecies are documented herein from three recognized lithofacies that share a complex mixed-affinity depositional architecture: basinal fine-grained marine-deltaic clays and silts of the Yuha Formation (Remeika, 1998a) sourced from the Gulf of California, delta-plain arenites of the progradational Palm Spring Formation (Woodring, 1931) sourced from the Colorado Plateau, and locally-derived syn-extensional fluviatile facies distributions of medial alluvial fan sandstones mapped regionally as the Ocotillo Formation (Remeika, 1992, 1997), sourced from the Canebrake Conglomerate (Dibblee, 1954). Isolated footprints, sets of tracks, and lesser trackways are relatively common, concentrated on beach clays or multiple flood-plain depositional paleosurfaces (subaerially-exposed mudflats) as either positive ceiling molds or negative floor casts. Their abundance confirms an importance as a consistent rather than occasional resource in the fossil record and proves that, under certain conditions, a discrete depositional package (basin-margin) can be a favorable repository of preferentially preserved vertebrate tracks.

ABBREVIATIONS

The following abbreviations are acronyms for institutions and repositories of ichnites cited herein: **IVCM** –vertebrate paleontology collections previously housed in the Imperial Valley College Museum, El Centro, California;

ABDSP –vertebrate paleontology collections of the California Department of Parks and Recreation, Colorado Desert District, Anza-Borrego Desert State Park, Borrego Springs, California; **SRC** –Stout Research Center and paleontology laboratory, Anza-Borrego Desert State Park, Borrego Springs, California. Stratigraphically-controlled Anza-Borrego Zones, utilizing lithologic markers, after Downs and White (1968). North American Land Mammal Age chronology after Repenning (1987). Identifications herein employed and emended follow the tentative binomial synonymy of avian and mammaloid paleoichnologic classifications after Vialov (1965, 1966), Aramayo and Manera de Bianco (1987, 1996), Leonardi (1987), and Sarjeant and Langston (1994) and attempts to preserve the original ichnogenera assignations following recommendations set forth in Article 23.1 of the International Code of Zoological Nomenclature, Fourth Edition. The Greek affix *–ichnum* (= *-ichnium*), meaning "*trace fossil of a …*" is preferred in most instances, and is emended herein in order to preserve the neutrality of the masculine suffix *–ichnus*. All specimen numbers preceded with a "V" represent ABDSP vertebrate specimens. Specimen numbers followed by an "A" represent plaster cast replicas.

GEOLOGIC SETTING

Setting. – The Vallecito-Fish Creek Basin is a 373 km^2 upper-plate syn-rift half-graben located 43 km south of Borrego Springs, California (Figure 1). Footprint-bearing strata are located along the north-central basin-margin. This area contains an organization of thick asymmetric sedimentary sequences including fault-bounded coarse-grained marginal conglomerates and finer-grained axial/central flood-basin paleofacies distributions that preserve unique ephemeral ichnocoenosis represented by the Fish Creek Canyon Ichnofauna. Altogether, the Miocene-Pleistocene basin-fill geometry represents > 5,000 m of nonmarine, marine, deltaic, and syn-deposited alluvial fan deposition exposed throughout the Carrizo, Fish Creek, and Vallecito Badlands. Sediments are vertically-stacked and shingled, and generally dip west in response to dip-slip activity on the Elsinore Fault Zone east of the presumed breakaway zone of the Western Salton Trough Detachment (Remeika, 1995). Due to its structural intactness, the Vallecito-Fish Creek Basin yields one of the most accessible and best preserved Neogene stratigraphic/paleontologic packages in North America (Remeika and Lindsay, 1992; Remeika et al., 1995; Remeika, 1997). Deposits of the Vallecito Badlands have been subjected to intensive study and fossil collecting since the 1930's by investigators of the American Museum of Natural History, Los Angeles County Museum of Natural History, Imperial Valley College Museum, and Anza-Borrego Desert State Park. This has resulted in well established lithostratigraphy (Downs and White, 1968; White et al., 1991; Remeika, 1995, 1997, 1998a), and magnetostratigraphy (Opdyke et al., 1977; Johnson et al., 1983), especially of the terrestrial deposits between the Fish Creek and Vallecito Badlands. These nonmarine sediments span the Plio-Pleistocene boundary, and are well over 2,000 m thick. Fossil vertebrates are plentiful, and range throughout the alternating marginal/basinal sandstones and finer-grained lacustrine sediments, providing a local record of evolution, immigration, and extinction for the past 2-3 million years.

Study area. – Vertebrate tracksites occur in multiple stratigraphic levels of a proximal flood-plain paleoenvironment between Hanging Tracks Wash (ABDSP 1727) in the North Fork of Fish Creek Wash and Arroyo Tapiado (ABDSP 1750) in the Vallecito Badlands (Remeika, 1993).

Stratigraphic framework. – The Yuha Formation consists of terrigenous sediments supplied by the ancestral Colorado River into a marginal-marine, tidally-dominated, delta-front environment of the northernmost Gulf of California (Remeika, 1998a). It is distinguished by the infrequent presence of siliciclastic-carbonate, epifaunal oyster-anomiid-dominated coquina beds separated by thick stratigraphic intervals of unfossiliferous, rhythmically-alternating couplets of fine-grained gypsiferous claystone and siltstone. The progradational stacking of rhythmites is laterally-persistent, and a distinctive feature where they occur in upward-coarsening cycles capped by arenites and/or coquina. The Yuha Formation interfingers with nonmarine arenites of the Palm Spring Formation.

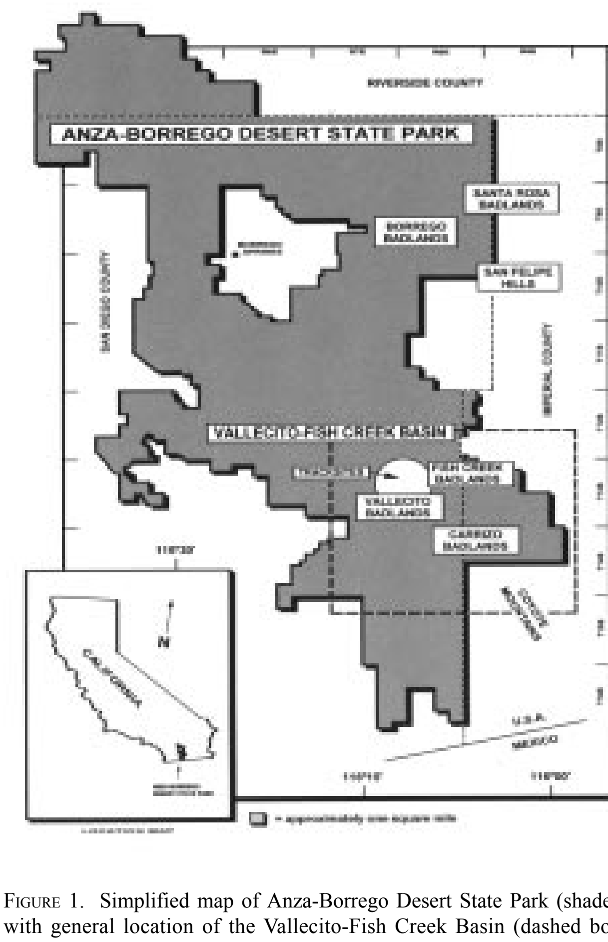


FIGURE 1. Simplified map of Anza-Borrego Desert State Park (shaded), with general location of the Vallecito-Fish Creek Basin (dashed box), location of specific badlands areas (solid boxes), and vicinity of tracksites (solid circle).

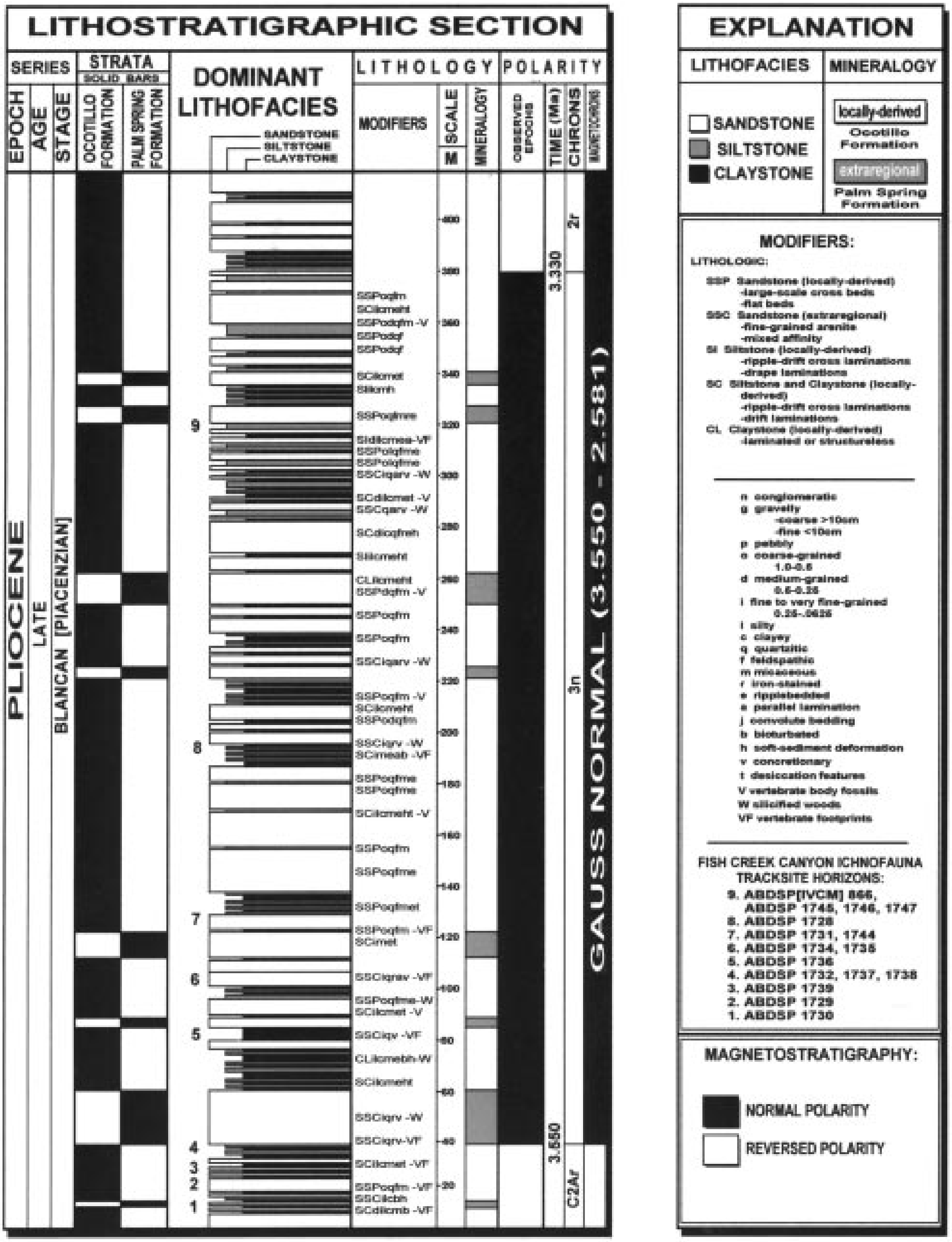


FIGURE 2. Composite lithostratigraphy of the basin-margin section between Fish Creek Canyon and Arroyo Seco del Diablo. The distribution of magnetized polarity epochs is shown to the right of the measured column.

The Palm Spring Formation is an extensively-exposed delta-plain deposit debouched by the ancestral Colorado River across the subsiding Salton Trough basin-center. In the Vallecito-Fish Creek Basin, this conspicuous lithofacies is 2,500 m thick (Dibblee, 1954). It represents deltaic progradation and maturation, with increased sediment yield. Sediments include extraregional pale pink to cream-colored, fine to very fine-grained, massive, concretionary, quartzitic arenites and gravelly sandstones with a common vertical pattern of zonation, punctuated stratigraphically by subordinate brown-colored, ripple-laminated, gypsiferous overbank claystones and siltstones. The high percentage of arenites resulted from current-deposited bedload of paleochannel, point bar, or sheetflood deposits that contain cross-bedding structures and textural features are indicative of an outgrowth from a highly meandering fluvial system (Remeika, 1997). The result is relatively persistent, uniform, multilateral arenites that are distinctive in outcrop, oftentimes forming prominent strike ridges. Along the basin-margin, the Palm Spring Formation interfingers with locally-derived sandstones of the Ocotillo Formation.

The Ocotillo Formation is a vertically-stacked, west-southwest thickening sequence of fluvially-deposited medium to coarse-grained alluvial fan sandstones and finer-grained sediments. Exposures in the Fish Creek Badlands represent the medial package of a strongly asymmetric sediment-thickness distribution shed from Canebrake Conglomerate host sequences. Depending upon location, gradation ranges from crudely-bedded, massive granitoid megaboulders to conglomeratic sandstones. Basinward, this unit is restricted by short transport distances along the subsiding axis, and shares an unconfined proximal to distal sandstone-dominated flood-plain relationship with the Palm Spring Formation. Distribution of sediments was controlled by a hydrodynamic regime promoted by high-energy flash flood and related fluvial processes which ultimately transported sands out of channels and across an expansive proximal flood-plain (Remeika, 1997). Gray-colored sandstones and siltstones dominate this sequence, interspersed with several easily distinguished reddish-brown arenitic tongues from the delta-plain. The high-energy sandstone sequences are generally multistory, sheet-like, and unconfined to broadly lenticular geometries with scoured or steeply channelized erosion surfaces. Small-scale planar and broad trough crossbedding, and parallel-laminated sandstones capped by suspension-deposited fines composed of current ripple-laminated claystone/sandstone dominate this setting. Olive-green micaceous silty claystone mud drapes suggest waning flow velocities. Subaerial indicators of exposure on paleosurfaces include desiccation cracks, raindrop impressions, low-energy wave- and adhesion-ripples, run-off channels and rills, and occurrences of a variety of trace fossils including vertebrate footprints.

Age. – Sedimentary deposits of the Vallecito-Fish Creek Basin cross several magnetic zones of both normal and reversed polarity. A normal remnant magnetic signature is documented in the eastern Vallecito Badlands between Fish Creek Canyon and Arroyo Seco del Diablo (Opdyke et al., 1977; Johnson et al., 1983) (Figure 2). This signature is interpreted to represent the lower normal epoch in the Gauss normal polarity magnetochron. This is bracketed above the Gilbert reversed magnetochron and below two short reversal intervals possibly matching the Mammoth and Kaena magnetosubchrons in the Gauss Normal Chron. An alternate correlation is with the upper normal epoch in the Gauss Normal Chron. This is based on a re-evaluation of the normal epoch at the top of the Vallecito Badlands section interpreted by Opdyke et al. (1977), and Johnson et al. (1983) to be either the Jaramillo or Olduvai normal magnetochrons (Remeika, 1999). It is entirely possible that it represents the Brunhes. Future refinements in the direction of magnetostratigraphy will undoubtedly resolve this problem. Following Johnson et al. (1983), either correlation is consistent with a Pliocene age assignment for the Fish Creek Canyon Ichnofauna (Blancan II-V), and places the age of Fish Creek Canyon at about 3.5 Ma (Blancan III; Cande and Kent, 1995), and Camel Ridge at about 3.3 Ma (Blancan III; Cande and Kent, 1995). The older tracksites ABDSP 1726, 1727, 1740, and 1741 occur in reversely magnetized sediments between the Nunivak and Cochiti normal magnetochrons in the Gilbert Reversed Chron (Joseph C. Liddicoat, written comm., 2001). This correlation places the age of Hanging Tracks Wash at about 4.3-4.5 Ma (Blancan II; Cande and Kent, 1995). The younger tracksites ABDSP 1748, 1749, and 1750 occur above the 2.58 Ma Gauss/Matuyama boundary (Blancan IV-V; Cande and Kent, 1995) in Arroyo Tapiado. This determination is supported by two volcanic ash beds that bracket the tracksites (Anza-Borrego Zone 46); the lowermost ash yields a fission-track date of 2.3 + 0.4 Ma (Johnson et al., 1983). Regionally, the western Vallecito Badlands may be synchronous to the Borrego Badlands of northern Anza-Borrego, constrained to the early Pleistocene (Irvingtonian I-II) based on identified and correlated tephrochronology (chemical fingerprinting of the Bishop and Thermal Canyon ash beds), applied magnetostratigraphy (presence of the Jaramillo normal magnetosubchron and the Brunhes Normal Chron), and presence of age-diagnostic ostracodes (such as *Limnocythere bradburyi*) and vertebrates (*Equus bautistensis*, *Camelops huerfanensis*, and *Mammuthus imperator*) (Remeika and Jefferson, 1993; Remeika and Beske-Diehl, 1996; Remeika, 1998b).

FISH CREEK CANYON ICHNOFAUNA

The first vertebrate tracksite discovered in the basin is Camel Ridge ABDSP [IVCM] 866 (Miller et al., 1982a, b) (Figure 3). The majority of footprints are tracks of hoofed didactyl llamoids yielding two distinct populations represented by the ichnospecies *Lamaichnum borregoensis*, measuring from 12 cm in length, and *Megalamaichnum albus* measuring from 17 cm in length. These compare favorably with the morphology and size generally attributable to the Pliocene trackmakers *Hemiauchenia macrocephala*, and *H. blancoensis*. In addition, small ansiodactyl bird tracks (ichnospecies *Gruipeda diabloensis*), a feloid footprint (ichnospecies *Pumaeichnum stouti*), and the musteloid

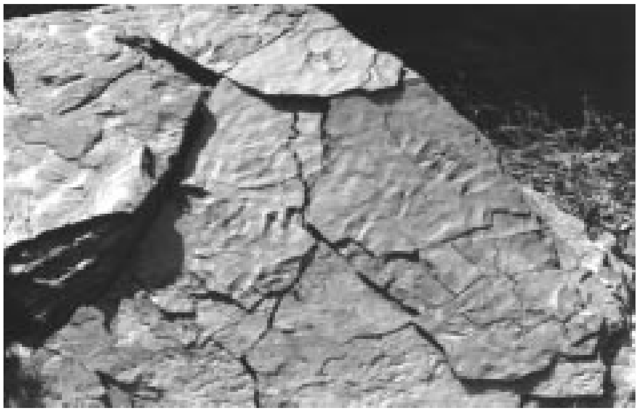


FIGURE 3. General view of the Camel Ridge tracksite (ABDSP [IVCM] 866), featuring well-preserved llamoid natural mold footprint impressions of *Lamaichnum borregoensis* Remeika, 1999 in hardened claystone. Track horizon 9. Individual impressions measure about 11.8 cm in length, and about 10.5 cm in width.

ichnospecies *Mustelidichnum vallecitoensis* also occur. Three other tracksite discoveries in the Fish Creek Badlands (Stout et al., 1987; Stout and Remeika, 1991) (ABDSP 1727, 1728, and 1729) yield a canoid, and large and small llamoids. These are in close proximity to a densely-trampled megatracksite (ADBSP 1730) dominated by monodactyl equoid tracks of the ichnospecies *Hippipeda downsi*. ABDSP 1732 is significant, yielding footprint impressions of three ichnotaxa on a single sandstone panel. The isolated natural casts exhibit manus and pes toe and pad digitigrade impressions of a feloid (ichnospecies *Pumaeichnum milleri*), a canoid with claw marks (ichnospecies *Chelipus therates*), and an isolated plantigrade footprint of a probable heavy-footed gomphotherioid trackmaker (ichnospecies *Stegomastodonichnum garbanii*). This footprint has an overall length of 38 cm, an overall breadth of 28 cm, and is impressed into the strata 13.5 cm. At present, twenty-four tracksites are known from the basin, with the largest density impressed between Arroyo Seco del Diablo and the North Fork of Fish Creek Wash.

SYSTEMATIC PALEOICHNOLOGY

DIVISION VERTEBRATICHNIA Vialov, 1966
CLASS AVIPEDIA Vialov, 1966
MORPHOFAMILY GRUIPEDIDAE Sarjeant and Langston, 1994

Ichnogenus *Gruipeda* Panin and Avram, 1962
Type ichnogenus.- *Gruipeda* Panin and Avram, 1962:

Diagnosis (emended after Sarjeant and Langston, 1994).- The ichnogenus *Gruipeda* includes avian footprints that exhibit morphological characters attributable to the Ralliformes, Charadriiformes, and the Ciconiiformes. *Gruipeda* embraces avian footprints showing four digits, three (II to IV) pointing forward and the fourth (I) pointing or directed posteriorly, its axis may coincide with, or be at an angle to, that of digit III. Digits united or separate proximally. Webbing not present.

Ichnospecies *Gruipeda diabloensis* Remeika, 1999
V6107, V6263, V6264, V6265, V6266, V6267, V6268
(Figure 4)

bird tracks, Miller et al., 1982a: poster session, 1982b: unpaginated.
shorebird tracks of *Pluvialis* and *Charadrius vociferous* (Hildegarde Howard, pers. comm., 1984) White et al., 1991: 9.
Avipeda sp. cf. *Calidris* sp. (sanderling track) Remeika et al., 1995: 90.
Avipeda sp. cf. *Tringa* sp. (sandpiper track) Remeika et al., 1995: 90.
Avipeda sp. cf. *Calidris* sp., and *Tringa* sp. Remeika, 1995: 22; Remeika, 1997: I-18.
fossil avian tracks and trackways Buchheim et al., 1999: 47-52, Figure 2, Figure 3, c-d, Figure 4, a-c, 57.
Gruipeda diabloensis Remeika, 1999: 44, Figure 10, 63.

Holotype.- ABDSP [IVCM] 866/V6107 (Figure 4). Avian trackway faintly impressed on what used to be a moist subaerially-exposed micaceous silty claystone bedding plane surface. Footprints were selected because the impressions are deep enough to leave a clear outline, and retain significant characteristics representative of the majority of footprint impressions. Specimen remains uncollected *in situ.*

FIGURE 4. Photograph of a well-preserved avian *Gruipeda diabloensis* Remeika, 1999 natural mold trackway impression (V6107) in hardened claystone from Camel Ridge. Track horizon 9. Individual footprint impressions measure between 1.3-1.6 cm in digit length.

Additional material.- Paratypes, ABDSP 1745/V6263-V6268, and ABDSP 1739/V6269 (unfigured). Specimens accessioned into the fossil vertebrate collections of the SRC. Additional paratypes remain uncollected and unnumbered *in situ* (Figure 5).

FIGURE 5. Close-up photograph of a set of avian (*Gruipeda diabloensis*) tracks as part of a natural mold trackway impression in hardened claystone from Camel Ridge (unnumbered *in situ*). Track horizon 9. Digit III measures approximately 1.6 cm in length for scale. Hammer head also for scale (10 cm).

Etymology.- Small avian footprints, named after Arroyo Seco del Diablo, site of discovery.

Diagnosis.- Type specimen represents obligate bipedal footprints made by an ansiodactyl avian trackmaker. Footprints of small size, exhibiting four slender, well-defined pedal digits (toes), one of which (III) is directed forward, II and IV directed outward curving anteriorly at a low angle, and I (hallux) directed backward, and short. The impressions of digits II and IV are similar in length, biconvex, tapering to a pointed tip (claw). Sharp claw on each digit although difficult to identify on the impression. Digit III is longer. Digit I is smaller and slender. The axis of digit I corresponds with, or may be slightly offset from, that of digit III. The average interdigital divarication between digits II and III is 74º and between III and IV is 54º. The impressions of digits I to IV are united proximally. Representative footprints are part of a narrow trackway; stride short. No indication of webbing between the digits.

Dimensions.- Breadth of trackway 3.0 cm; stride length 9.7 cm. Length of digits: I, 0.6-0.7 cm; II, 1.3 cm; III, 1.6 cm; IV, 1.5 cm.

Discussion.- Ansiodactyl avian footprints of *Gruipeda diabloensis* occur in direct association with the llamoids *Lamaichnum borregoensis*, *Megalamaichnum albus*, the musteloid *Mustelidichnum vallecitoensis*, and the feloid *Pumaeichnum stouti* at Camel Ridge. The uniformity of preservation indicates that the footprints were ephemeral, impressed within a short period of time. Since there is no indication of mudcracks, the clay was moist enough and not exposed to the drying effects of air for a prolonged period of time prior to burial. The tracks seem to have been made by several individuals of the same species walking in random variable directions.

Locality.- Camel Ridge (Anza-Borrego Zone 35), Arroyo Seco del Diablo, Vallecito-Fish Creek Basin, approximately 34 km east of Canebrake, California. The exact locality ABDSP [IVCM] 866, is on file at the SRC. A second locality, ABDSP 1745, represents the northern extension of Camel Ridge. A third locality, ABDSP 1739 reported by Buchheim et al. (1999: 49, Figures 3, c-d; 50, Figures 4, a-c), occurs in Fish Creek Wash, and is on file at the SRC. The avian footprints (V6269) at this tracksite remain uncollected *in situ*.

Horizon.- Fluvial thin-bedded micaceous silty claystone interbed of the Ocotillo Formation. Track horizon 9.

Age.- Holotype and paratypes V6263-V6269: late Pliocene (Blancan III).

Possible affinity of the trackmaker.- Fossil footprints of *Gruipeda diabloensis* were informally compared to modern *Calidris alba* (sanderling) and *Calidris mauri* (sandpiper) avian shorebird tracks (Paul Jorgensen, pers. comm., 1994). This was based on the hallux being reduced to where it registers no impression or only a minute impression, and therefore assigned to the blanket ichnogenus *Avipeda* following the synonymy of Vialov (1966), and Scrivner (1984). Upon further scrutiny, the size and morphology of *Gruipeda diabloensis* closely resembles footprints of the modern calidridine least sandpiper *Calidris minutilla*.

CLASS MAMMALIPEDIA Vialov, 1966
ORDER CARNIVORIPEDIDA Vialov, 1966
MORPHOFAMILY MUSTELIPEDIDAE ichnofam. nov.

Ichnogenus *Mustelidichnum* Aramayo and Manera de Bianco, 1987
Mustelidichnum Aramayo and Manera de Bianco, 1987: 535, 544 Figures 4a, 4b.

Type ichnospecies.- *Mustelidichnum enigmaticum* Aramayo and Manera de Bianco, 1987: 535, 544 Figures 4a, 4b, late Pleistocene (Lujanian), Argentina.

Emended diagnosis (based on Aramayo and Manera de Bianco, 1987).- Intermediate-size plantigrade to digitigrade obligate quadruped pentadactyl footprint exhibiting five sharply-clawed digits, each with a spheroidal to ovoidal digital pad. There is no separation between claw and digital pad giving each pad a characteristic pointed appearance. Manus typically smaller than pes. Both manus and pes roundish, slightly wider than long. Pes partially webbed, with webbing impressed between the central digits. Digital pads elongated and crowded, aligned in a conspicuous 1-3-1 spacing, with outer digits I and V separated slightly from central digits II-IV. This asymmetric placement of digits and the presence of a chevron-shaped interdigital pad are diagnostic characteristics of the carnivorian family Mustelidae. The interdigital pad impression may be subquadrangular, commonly deeply-lobed, fused, and continuous.

Ichnospecies *Mustelidichnum vallecitoensis* ichnosp. nov.
V6280
(Figure 6)

Holotype.- ABDSP 1745/V6280 (Figure 6). Described specimen is an isolated and undistorted left pes musteloid footprint impression preserved on what used to be a moist subaerially-exposed micaceous silty claystone bedding plane surface. Specimen is accessioned into the fossil vertebrate collections of the SRC.

Additional material.- Musteloid footprint impressions that compare favorably to V6280 have not been found.

Etymology.- In reference to sedimentary exposures of the Vallecito Badlands above the Palm Spring Formation that yield many significant vertebrate fossils.

Diagnosis.- Type specimen is preserved as a natural mold (concave epirelief) on ripplebedded, very fine-grained micaceous claystone. Represents a left pes paw-print of an intermediate-size plantigrade to digitigrade musteloid trackmaker. The paw-print exhibits five well-developed digits (I-V), each with a spheroidal to ovoidal digital pad. Central digits (II, III, and IV) are parallel; outer digits (I and V) are offset and angle slightly outward. Arrangement of the digits forms a single semicircular arc in front of the interdigital pad. Digital pad impressions are of equal or similar size, with digit I subordinate to the central digits II-IV. Each digit possesses a non-rectractile acuminate claw that may or may not register. There is no separation between claw and digit. Claw marks indistinct, and may give each digit an elongated, pointed appearance. Webbing normally present, especially in the pes, impressed between digits. The interdigital pad is large, deeply lobed, and asymmetric with an elongated proximal (metatarsal) heel. The anterior of the interdigital pad is chevron-shaped, longer than wide.

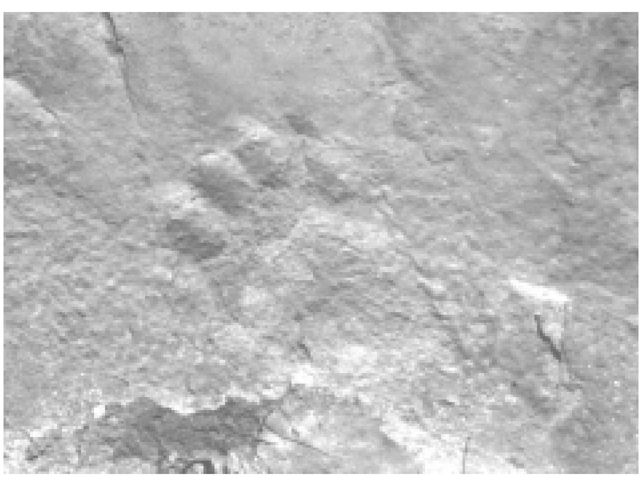


FIGURE 6. *Mustelidichnum vallecitoensis* (ichnosp. nov.): isolated natural mold impression of a left pes paw-print (V6280) of a musteloid in hardened claystone from Camel Ridge. Track horizon 9. Length of digit III is 2.2 cm for scale.

Dimensions.- Type specimen (left pes): overall print length 11.5 cm; overall print breadth 8.5 cm. Length of digits: I, 2.3 cm; II, 2.0 cm; III, 2.2 cm; IV, 2.7 cm; and V, 2.0 cm. Breadth of digits: I, 1.4 cm; II, 1.3 cm; III, 1.3 cm; IV, 1.5 cm; and V, 1.5 cm. Interdigital pad length, 7.7 cm; interdigital pad breadth, 6.5 cm.

Locality.- Camel Ridge (Anza-Borrego Zone 35), Arroyo Seco del Diablo, Vallecito-Fish Creek Basin, approximately 34 km east of Canebrake, California. The exact locality, ABDSP 1745, is on file at the SRC.

Horizon.- Fluvial, thin-bedded, micaceous silty claystone interbed of the Ocotillo Formation. Track horizon 9.

Age.- Late Pliocene (Blancan III).

Possible affinity of the trackmaker.- The morphological attributes of the ABDSP 1745 ichnotrack not only resembles those made by an aquatic mustelid but represents the first unequivocal track evidence ever reported in California. Although somewhat speculative, the only likely candidate recognized from the Vallecito-Fish Creek Basin may be the small-clawed river otter *Satherium piscinarium* (Remeika et al., 1995). *S. piscinarium* is well-represented in North America during the Blancan (Kurtén and Anderson, 1980) and may be expected in the Camel Ridge lacustrine deposits although its body-fossil record has not so far been reported. From the positive evidence thus far gathered, *S. piscinarium* is most likely to be the trackmaker.

MORPHOFAMILY CANIPEDIDAE ichnofam. nov.

Ichnogenus *Chelipus* Sarjeant and Langston, 1994

Chelipus Sarjeant and Langston, 1994: 28-29; Remeika, 1999: 42-43, 63.

Type ichnospecies.- *Chelipus gracilis* Vialov, 1965 (= *Bestiopeda gracilis* Vialov, 1965: 113; Vialov, 1966: 134-135, 202, Figure 2), Miocene (Burdigalian), Ukraine.

Other ichnospecies.- *Chelipus therates* Remeika, 1999: 42-43, Figure 8, Pliocene (Blancan), ABDSP, San Diego County, California; *Pehuencoichnum gracilis* Aramayo and Manera de Bianco, 1987: 534-535, 543 Figures 3a, 3b, late Pleistocene (Lujanian), Argentina.

Emended diagnosis.- The morphofamily Canipedidae differs from the blanket sister taxon Carnivoripedidae of Vialov (1966), embracing only small plantigrade to digitigrade obligate quadruped tetradactyl canoid footprints exhibiting four digits (II-V), each with a spheroidal to ovoidal digital pad, sharp permanently extended claws are present and normally impressed. Central digits (III and IV) parallel and symmetrical, outer digits (II and V) proximally divergent at angles of less than 20°.

Discussion.- Sarjeant and Langston (1994) introduced *Chelipus* as a new ichnogenus defined by footprints in which the claws are permanently extended, specifically in footprints of canoids. This distinction follows Sarjeant and Langston's (1994) division of Vialov's (1965, 1966) blanket ichnogenus *Bestiopeda*. Ichnotracks of *Pehuencoichnum gracilis* (Aramayo and Manera de Bianco, 1987: 534-535, 543 Figures 3a, 3b) reflect a footprint structure strikingly like that of a canoid rather than a feloid as originally assigned, and are certainly referable to *Chelipus* as a member of this ichnogenus.Footprints assigned to the ichnogenus *Chelipus* are gracile in size and morphology, barely within the lower limits of the modern juvenile *Canis lupus* (wolf) track dimensions, but differ in no significant way from modern footprints of a moderate-size coyote (*Canis latrans*). Registration of conspicuous claw marks and a triangular shaped interdigital pad are diagnostic characteristics of the carnivorian family Canidae and distinguishes this ichnogenus from feloid footprints. Footprint size and morphology of obviously synapomorphic characteristics shared with extant canoid carnivorous trackmakers, especially *Canis latrans* (coyote), suggests attribution to the ichnogenus *Chelipus* is very reasonable.

Ichnospecies *Chelipus therates* Remeika, 1999
V6276, V6276A, V6277, V6277A, V6278, V6278A, V6279
(Figure 7)

Canipeda sp. cf. *Borophagus* sp. (bone-eating dog track) Remeika et al., 1995: 90.
Canipeda sp. cf. *Borophagus* sp. Remeika, 1995: 24.
Chelipus therates, a likely canoid Remeika, 1999: 42-43, Figure 8, 63.

Holotype.- Left manus (ABDSP 1732/V6276) and a left pes (ABDSP 1732/V6277) (Figure 7). Footprint impressions represent an undistorted set of ichnotracks preserved as sandstone ceiling casts on the underside of a massive channel sandstone strike ridge panel. Plaster cast replicas (V6276A and V6277A) are accessioned into the fossil vertebrate collections of the SRC. Original specimens remain uncollected *in situ*.

Figure 7. Photograph of a well-preserved ceiling cast set of canoid tracks in sandstone from Fish Creek Canyon. Track horizon 4. *Chelipus therates* Remeika, 1999. Note larger load-bearing left manus footprint (V6276) and its relationship to the smaller left pes footprint (V6277). For scale, the manus is 6.4 cm in length and 5.9 cm in width.

Additional material.- Paratypes: one manus impression ABDSP 1731/V6278 preserved as an oblique sandstone ceiling cast. This specimen outcrops on strike with the holotype, exhibiting four claw marks registered in the footprint impression. A plaster cast replica (V6278A) is accessioned into the SRC. A second manus impression ABDSP 1736/V6279 is preserved as a sandstone ceiling cast (Figure 8). Due to the nature of exposure, it remains uncollected *in situ*.

Etymology.- Greek *chele*, claw; *pous*, foot; *therates*, hunter; in reference to a foraging carnivore that wanders about seeking food, hence "claw-footed hunter".

Diagnosis.- Type specimens are preserved in convex hyporelief, and represent manus and pes paw-prints of an intermediate-size digitigrade canoid trackmaker. The manus is noticeably larger than the pes. Paw-prints exhibit four well-developed digits (II-V), each with an elongate (long axis) spheroidal to ovoidal digital pad. Central digits (III and IV) are thick, exhibit bilateral symmetry, and give rise to a prominent non-retractile acuminate claw, fully extended. On the

Figure 8. Well-preserved ceiling cast impression of an isolated track of *Chelipus therates* Remeika, 1999 in claystone from Fish Creek Canyon. Track horizon 4. Note triangular-shaped interdigital pad configuration and presence of claw marks. Scale: same as used in Figure 7.

manus, only the tips of claws are impressed dependent on the substrate. Outer digits (II and V) angle slightly outward, are also thick, and possess non-retractile acuminate claws that may or may not register. Arrangement of the digits forms a single semicircular arc in front of the sole and heel pad. Digital pad impressions are of equal or similar size, longer than wide, and closely-spaced. Central digits may be smaller than outer digits. The interdigital pad is large, deeply lobed, and equilateral with one rounded lobe centered anteriorly, and two subordinate rounded lobes posteriorly positioned on either side of, and laterally stepped-down from, the central lobe. The overall pad shape is triangular. On the manus (load-bearing), the interdigital pad is large and crescent-shaped. On the pes, it is typically narrow or ovoid with a lack of space between digits and anterior edge. The leading edge tends to be convex. The overall shape of the manus and pes is rectangular, longer than wide.

Dimensions.- Holotype: left manus (V6276): overall print length 6.4 cm; overall print breadth 5.9 cm. Length of digits: II, 2.4 cm; III, 2.6 cm; IV, 2.6 cm; V, 2.5 cm. Breadth of digits: II, 1.5 cm; III, 1.5 cm; IV, 1.5 cm; V, 1.7 cm. Interdigital pad length, 2.5 cm; interdigital pad breadth, 3.3 cm. Observed claw length (manus): II, not present; III, 1.0 cm; IV, 0.7 cm; V, not present. Holotype: left pes (V6277): overall print length 6.0 cm; overall print breadth 4.7 cm. Length of digits: II, 1.9 cm; III, 2.2 cm; IV, 2.3 cm; V, 1.7. Breadth of digits: II, 1.4 cm; III, 1.2 cm; IV, 1.4 cm; V, 1.3 cm. Interdigital pad length, 2.0 cm; interdigital pad breadth, 2.5 cm. Pes claw marks not observed. Since only one set of tracks is preserved, the intergroup distance and stride measurements are not applicable herein.

Discussion.- Canoid impressions of *Chelipus therates* occur as a set of ichnotracks in direct association with *Lamaichnum borregoensis*, *Megalamaichnum albus*, *Pumaeichnum milleri*, and *Stegomastodonichnum garbanii*. Footprints are definitely doglike, with manus and pes registry identical in size and morphology parameters to those of a typical contemporary western coyote (*Canis latrans*). While correlation with extant *C. latrans* may be unjustified, the close correspondence in footprint structure and measurements is too obvious to require critical argument. Therefore, the trackmaker of *Chelipus therates* is an extinct coyote. The manus holotype V6277 compares favorably to isolated paratypes preserved in convex hyporelief, discovered at localities ABDSP 1731, and ABDSP 1736.

Locality.- Fish Creek Canyon (Anza-Borrego Zone 29), Vallecito-Fish Creek Basin, approximately 29 km southwest of Ocotillo Wells, California. The exact locality, ABDSP 1732, is on file at the SRC.

Horizon.- Thick-bedded, fine-grained fluvio-deltaic arenite deposit of the Palm Spring Formation. Track horizon 4.

Age.- Late Pliocene (Blancan III).

Possible affinity of the trackmaker.- Coyote-like canid body-fossils are reported from the Arroyo Seco Local Fauna (Remeika et al., 1995). Since the morphological attributes of the ABDSP 1732 sample ichnotracks are nearly indistinguishable from the extant western coyote *Canis latrans* (Table 1), a plausible candidate trackmaker may be *C. lepophagus*. This extinct coyote is well-represented throughout western North America during the late Blancan-early Irvingtonian, and is the direct ancestor of Irvingtonian-Recent coyotes (Kurtén and Anderson, 1980).

MORPHOFAMILY FELIPEDIDAE ichnofam. nov.

Ichnogenus *Pumaeichnum* Aramayo and Manera de Bianco, 1987

Pumaeichnum Aramayo and Manera de Bianco, 1987: 534; *Pumaeichnium* Remeika, 1999: 42.

TABLE 1. Measurements of manus and pes impressions of *Chelipus therates* [1] compared with modern western coyote footprint examples of *Canis latrans* [2] collected from Borrego Valley, California, and Mexican wolf footprint examples of *Canis lupus baileyi* [3] collected at the Living Desert Reserve, Palm Desert, California. ICN, ichnite; RM, right manus; LM, left manus; RP, right pes; LP, left pes; PL, print length; PB, print breadth; DL, digit length; DB, digit breadth; IPL, interdigital pad length; IPB, interdigital pad breadth. Measurements in centimeters (cm).

ICN	PL	PB	DLII	DLIII	DLIV	DLV	DBII	DBIII	DBIV	DBV	IPL	IPB
ABDSP 1732/V6276												
LM 1	6.0	5.9	2.4	2.6	2.6	2.5	1.5	1.5	1.5	1.7	2.5	3.3
ABDSP 1732/V6277												
LP 1	6.0	4.7	1.9	2.2	2.3	1.7	1.4	1.2	1.4	1.3	2.0	2.5
Canis latrans												
LM 2	5.5	5.8	1.9	2.0	2.1	1.9	1.2	1.4	1.4	1.3	2.3	3.0
RM 2	5.5	5.7	1.9	2.1	2.1	1.9	1.1	1.4	1.3	1.3	2.3	2.9
LP 2	5.4	4.7	1.9	2.0	2.0	1.8	1.3	1.2	1.3	1.2	2.0	2.5
RP 2	5.3	4.7	1.8	2.0	2.0	1.8	1.2	1.2	1.3	1.2	2.1	2.4
Canis lupus baileyi												
RM 3	7.3	7.4	2.6	2.7	2.5	2.1	1.7	1.6	1.6	1.3	3.2	4.2
RP 3	6.7	6.5	2.2	2.7	2.7	2.1	1.4	1.7	1.4	1.2	2.8	3.7

Type ichnospecies.- *Pumaeichnum biancoi* Aramayo and Manera de Bianco, 1987: 534, 543 Figures 2a, 2b, late Pleistocene (Lujanian), Argentina (=*Bestiopeda bestia* Vialov, 1966: 128-129, 202 Figure 1), Miocene (Budigalian), Ukraine.

Other ichnospecies.- *Pumaeichnium milleri* Remeika (1999: 42, Figures 6-7), Pliocene (Blancan), ABDSP, San Diego County, California.

Emended diagnosis.- The morphofamily Felipedidae differs from the blanket sister taxon Carnivoripedidae of Vialov (1966), embracing plantigrade, semi-plantigrade to digitigrade obligate quadruped tetradactyl feloid footprint impressions exhibiting four digits (II-V), each with a spheroidal to ovoidal digital pad forming a single semicircle arc in front of the interdigital pad sole and heel impressions. Digital pads are of equal or similar size. Impressions of claw tips are usually absent. Aramayo and Manera de Bianco (1987) restricted the ichnogenus *Pumaeichnum* as a junior synonym of the ichnogenus *Bestiopeda* Vialov (1965: 112; 1966: 128), emending *Pumaeichnum* to a specific ichnogenus that embraces only feloid footprints and trackways.

Discussion.- The morphology of the whole foot structure, as indicated by the preserved footprint impressions, makes their systematic assignment to the ichnogenus *Pumaeichnum* very strong. Diagnostic feloid footprint characteristics, such as arrangement of the digits and pad impressions, deeply bilobed anterior/trilobed posterior interdigital pad heel configuration, and impressions with claws normally retracted and claw tips usually absent except in the case of aberrant canid-like feloid tracks, is a trait of the carnivorian family Felidae and distinguishes footprints assigned to this ichnogenus from those of typical canoid footprints. This recognition is significant and strongly suggests a predatory feloid trackmaker, intermediate in size, based on the morphometric analysis of the footprints as compared, for example, to the existing felids *Lynx rufus* (western bobcat) and *Felis concolor* (western mountain lion).

Ichnospecies *Pumaeichnum milleri* Remeika, 1999
emend. Remeika, nov.
V6106, V6106A, V6282, V6282A, V6284
(Figure 9)

Pumaeichnium milleri a likely feloid Remeika, 1999: 42, Figures 6-7, 63.

Holotype.- ABDSP 1732/V6106 right manus (Figure 9), and ABDSP 1732/V6282 left pes (Figure 10) footprint impressions preserved as an undistorted set of ichnotracks on the underside of a massive channel sandstone strike ridge panel. The manus specimen is accessioned into the fossil vertebrate collections of the SRC. The pes impression remains uncollected *in situ*. Plaster cast replicas (V6106A and V6282A) are accessioned into the SRC.

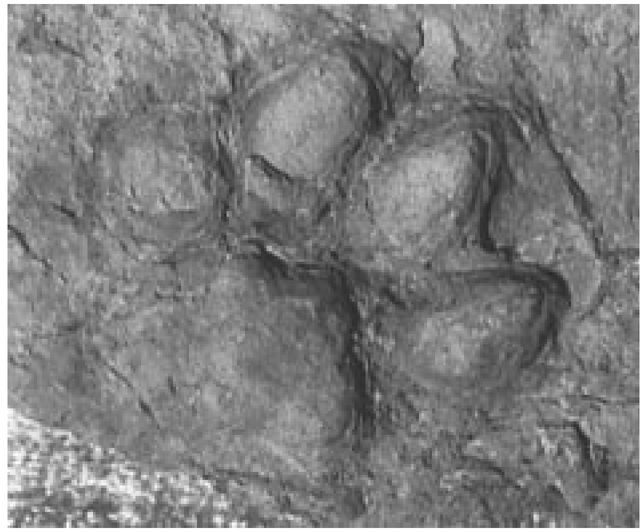


FIGURE 9. Well-preserved feloid right manus ceiling cast impression of *Pumaeichnum milleri* Remeika, 1999 (V6106) in sandstone from Fish Creek Canyon. Track horizon 4. Note deeply bilobed anterior/trilobed posterior interdigital pad configuration and absence of claw marks. For scale, the manus is 6.1 cm in length and 6.3 cm in width.

Additional material.- Paratype ABDSP 1732/V6284 is an isolated manus footprint impression outcropping on the same sandstone panel. It remains uncollected *in situ*.

Etymology.- Fossil feloid footprint impressions, named in honor and memory of George J. Miller, who served as Curator of Paleontology at the IVCM.

Diagnosis.- Type specimens are preserved in convex hyporelief, and represent right manus and left pes paw-prints registered as a set of ichnotracks of a lynx-size digitigrade feloid trackmaker. The manus is noticeably larger than the pes. Paw-prints exhibit four well-developed digits (II-V), each with a spheroidal to ovoidal digital pad. Central digits (III

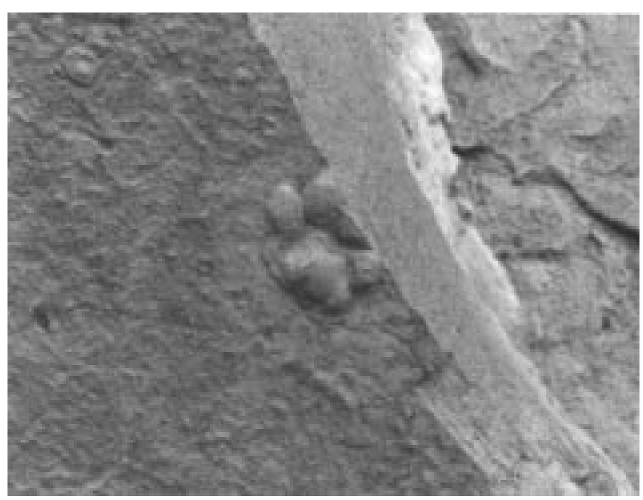


FIGURE 10. Partially-preserved feloid left pes ceiling cast impression of *Pumaeichnum milleri* Remeika, 1999 (V6282) in sandstone from Fish Creek Canyon. Track horizon 4. For scale, the pes is 4.5 cm in length and 5.5 cm in width.

and IV) are parallel and asymmetric; outer digits (II and V) angle slightly outward. Arrangement of the digits forms a single semicircular arc in front of the interdigital heel pad. Digital pad impressions are of equal or similar size, almost wider than long. Acuminate claws retractile; impressions of claw tips usually absent. The interdigital pad is large, deeply lobed, and equilateral especially in the pes, with two lobes anteriorly, and three lobes posteriorly. In cross-section, the central lobe II of the interdigital pad is equilateral or slightly diminished in profile when compared with lobes I and III. In longitudinal cross-section, the interdigital pad anterior heel lobes are canted higher forward and squared off in comparison to the lesser posterior heel lobes. The overall shape of the manus and pes is round or wider than long. Digits II, III, IV, and V of the manus are spread more than in the pes; manus digits II, III, and IV are imprinted deeper than digit V indicating a right manus, and that they are the principal load-bearing digits. The left pes tends to be wider than long.

Dimensions.- Holotype: right manus (V6106): overall print length 6.1 cm; overall print breadth 6.3 cm. Length of digits: II, 2.5 cm; III, 2.7 cm; IV, 2.4 cm; V, 1.6 cm. Breadth of digits: II, 1.2 cm; III, 1.2 cm; IV, 1.1 cm; V, 1.2 cm. Interdigital pad length, 2.7 cm; interdigital pad breadth, 3.6 cm. Holotype: left pes (V6284): overall print length 4.5 cm; overall print breadth 5.5 cm. Length of digits: II, 1.6 cm; III, 1.4 cm; IV, indeterminate; V, 1.5 cm. Breadth of digits: II, 1.2 cm; III, 1.2 cm; IV, 1.1 cm; V, 1.0 cm. Interdigital pad length, 1.9 cm; interdigital pad breadth, 3.3 cm. Since the impressions represent only a set of ichnotracks, the intergroup distance and stride measurements are not applicable herein.

Discussion.- Feloid footprint impressions occur in direct association with ichnotracks of *Lamaichnum borregoensis*, *Megalamaichnum albus*, *Chelipus therates*, and *Stegomastodonichnum garbanii*. Footprints are definitely catlike, being larger than modern tracks of *Lynx rufus* (western bobcat), yet smaller in size than the ichnotrack of *P. stouti* and modern tracks of *Felis concolor* (western mountain lion).

Locality.- Fish Creek Canyon (Anza-Borrego Zone 29), Vallecito-Fish Creek Basin, approximately 29 km southwest of Ocotillo Wells, California. The exact locality, ABDSP 1732, is on file at the SRC.

Horizon.- ABDSP 1732 is a prominent thick-bedded, fine-grained arenite bed, part of a multistoried sequence of fluvio-deltaic sediments deposited by the ancestral Colorado River as the Palm Spring Formation. Track horizon 4.

Age.- Late Pliocene (Blancan III).

Possible affinity of the trackmaker.- Cranial and postcranial elements found in partial articulation are referable to the lynx-size cat *Felis rexroadensis* reported from the Vallecito Creek Local Fauna (Remeika et al., 1995). Due to the robusticity of the footprints, a morphometric resemblance to *Lynx rufus* is ruled out. Since *Felis concolor* is a late Pleistocene (Rancholabrean)-Recent (Holocene) cat, the reasonable candidate trackmaker may be the intermediate lynx-sized *F. lacustris* which is conspecific to *F. rexroadensis*. *F. lacustris* is well-represented throughout western North America during the Blancan-early Irvingtonian (Werdelin, 1985). Table 2

TABLE 2. Measurements of manus and pes impressions of *Pumaeichnum milleri* [1], *P. stouti* [2], compared with modern western bobcat footprint examples of *Lynx rufus* [3, 4] collected from the coastal chaparral community of Camp Pendleton, California, and western mountain lion footprint examples of *Felis concolor* collected from Pine Valley [5] and Big Sur [6] California, respectively. ICN, ichnite; RM, right manus; LM, left manus; RP, right pes; LP, left pes; PL, print length; PB, print breadth; DL, digit length; DB, digit breadth; IPL, interdigital pad length; IPB, interdigital pad breadth; IND, indetermined. Measurements in centimeters (cm).

ICN	PL	PB	DLII	DLIII	DLIV	DLV	DBII	DBIII	DBIV	DBV	IPL	IPB
ADBSP 1732/V6106												
RM 1	6.1	6.3	2.5	2.7	2.4	1.6	1.2	1.2	1.1	1.2	2.7	3.6
ABDSP 1732/V6282												
LP 1	4.5	5.5	1.6	1.4	IND	1.5	1.2	1.2	1.1	1.0	1.9	3.3
ABDSP [IVCM] 866/V6285												
RM 2	6.8	7.0	2.7	2.8	2.4	1.4	1.8	1.8	1.8	1.4	3.5	5.3
Lynx rufus												
LM 3	5.0	4.5	1.7	2.0	1.9	1.6	1.1	1.0	1.0	1.1	2.0	2.8
LP 3	4.5	4.6	1.5	1.8	1.7	1.4	0.8	0.8	0.8	0.6	2.0	2.5
RM 4	5.0	4.2	1.5	1.6	1.5	1.4	0.9	0.9	0.9	0.7	2.6	3.2
RP 4	4.7	4.2	1.6	1.9	1.7	1.3	1.2	0.9	0.9	0.9	2.0	2.7
Felis concolor												
RM 5	9.8	8.8	3.0	2.7	2.7	2.5	1.7	1.7	1.6	1.5	4.5	5.2
LM 5	9.7	8.7	3.1	3.1	3.1	2.7	1.8	1.7	1.8	1.6	4.8	6.5
RP 5	9.9	8.2	3.0	3.0	3.0	2.5	1.8	1.8	1.7	1.4	4.0	5.2
LP 5	9.9	8.9	3.0	3.1	2.8	2.5	1.7	1.8	1.6	1.4	4.2	5.2
RM 6	7.7	8.8	3.0	2.6	2.6	2.3	1.5	1.6	1.7	1.3	4.6	6.0
LM 6	7.3	8.7	3.0	IND	IND	2.5	1.7	1.9	IND	1.6	4.3	6.3
RP 6	9.0	5.4	3.1	3.5	3.3	2.8	1.9	1.8	1.8	1.5	4.0	5.2
LP 6	8.1	8.2	3.0	3.0	2.9	2.7	1.7	1.9	1.9	1.4	4.0	5.0

measurements indicate the ichnospecies *P. milleri* is morphometrically divided between the genera *Lynx* and *Felis* yet exclusively shares a resemblance to lynxes and pumas. This is compelling evidence that *F. lacustris* may be the plausible candidate trackmaker.

Ichnospecies *Pumaeichnum stouti* ichnosp. nov.
V6285
(Figure 11)

footprints of Felis or immature *Smilodon* White et al., 1991: 9.
Felipeda sp. cf. ?*Smilodon* sp. (sabertooth track) Remeika et al., 1995: 90.
Felipeda sp. cf. *Felis* sp., or immature *Smilodon* sp. Remeika, 1995: 22.
Felipeda sp. cf. *Felis* sp. Remeika, 1997: I-18.

Holotype.- ABDSP 1745/V6285 (Figure 11). One isolated footprint impression of a right manus preserved as natural mold (concave epirelief) on ripplebedded, very fine-grained micaceous claystone. Specimen is accessioned into the fossil vertebrate collections of the SRC.

Additional material.- Feloid footprint impressions that compare favorably to V6285 have not been found.

Etymology.- The ichnospecies is named in honor of Betty W. Stout, for her generous and wide-ranging support of, and assistance to, the paleontologic program at ABDSP.

Diagnosis.- Type specimen is undistorted, preserved in concave epirelief, and represents a right manus paw-print of a puma-sized digitigrade feloid trackmaker. The paw-print exhibits four well-developed digits (II-V), each with a spheroidal to ovoidal digital pad. Central digits (III and IV) are parallel and asymmetric; outer digits (II and V) angle slightly outward. Arrangement of the digits form a single semicircular arc in front of the interdigital heel pad. Digital pad impressions are of equal or similar size, longer than wide. Acuminate claws may be retractile, yet claw tips are registered in the footprint impression directly joined to the anterior end of each digital pad. There is no separation between claw and pad. The interdigital pad is large, equilateral, and lobate, with two lobes anteriorly, and three lobes posteriorly. The overall shape of the pes is round or wider than long. Digits II, III, IV, and V of the manus are distinct and imprinted deeper than digit V, indicating a right manus, and that they are the principal load-bearing digits in this particular footprint impression.

FIGURE 11. Feloid right manus natural mold impression of *Pumaeichnum stouti* (ichnosp. nov.) (V6285) in hardened claystone from Camel Ridge. Track horizon 9. Hammer for scale (34 cm). The manus is 6.8 cm in length and 7.0 cm in width.

Dimensions.- Right manus (V6285): overall print length 6.8 cm; overall print breadth 7.0 cm. Length of digits: II, 2.7 cm; III, 2.8 cm; IV, 2.4 cm; V, 1.4 cm. Breadth of digits: II, 1.8 cm; III, 1.8 cm; IV, 1.8 cm; V, 1.4 cm. interdigital pad length: 3.5 cm; interdigital pad breadth: 5.3 cm.

Locality.- Camel Ridge (Anza-Borrego Zone 35), Arroyo Seco del Diablo, Vallecito-Fish Creek Basin, approximately 34 km east of Canebrake, California. The exact locality, ABDSP 1745, is on file at the SRC.

Horizon.- Fluvial, thin-bedded, micaceous silty claystone interbed of the Ocotillo Formation. Track horizon 9.

Age.- Late Pliocene (Blancan III).

Possible affinity of the trackmaker.- The skeletal-fossil record in the study area includes two large felid taxa (Remeika et al., 1995), although *Homotherium* sp., and *Smilodon gracilis* morphologically could not have produced the *Pumaeichnum stouti* paw-print. Furthermore, diagnostic criteria described herein for other ichnospecies (Table 2) is not characteristic of *P. stouti*, leaving only *Acinonyx* (*Miracinonyx*) *studeri* (Savage, 1960) as the likely candidate trackmaker. *A.*(*M.*) *studeri* is an extinct puma-size cheetah that inhabited the area during the early Irvingtonian (Jefferson and Tejada-Flores, 1995). Its range into the late Blancan III represents the earliest record of cheetah in the Pliocene of California. When taken into account, this is compelling evidence for the existence of a new ichnospecies.

ORDER PERISSODACTIPEDIDA Vialov, 1966
MORPHOFAMILY HIPPIPEDIDAE Vialov, 1966

Ichnogenus *Hippipeda* Vialov, 1966

Hippipeda Remeika, 1999: 43-44; Sarjeant and Reynolds, 1999: 14-15.

Type ichnospecies.- *Hippipeda aurelianis* Vialov, 1966: 137-138, 203, Figures 1-2, Neogene, Ukraine.

Other ichnospecies.- *Hippipeda* sp. A Scrivner, 1984: 173-175, Figure 38; Scrivner and Bottjer, 1986: 302, Figure 6A, late Miocene (Hemphillian), Death Valley, California.

Hippipeda sp. B Scrivner, 1984: 173, 176-177, Figure 39; Scrivner and Bottjer, 1986: 303, Figure 6B, late Miocene (Hemphillian), Death Valley, California. *Hippipeda* sp. C Scrivner, 1984: 173, 178-179, Figure 40; Scrivner and Bottjer, 1986: 303-304, Figure 6C, late Miocene (Hemphillian), Death Valley, California. *Hippipeda araiochelata* Sarjeant and Reynolds, 1999: 15-16, Plate 8, Figures 1-3, Figure 22, Plate 9, Figures 1-2, Miocene (Barstovian), San Bernardino County, California. *Hippipeda absidata* Sarjeant and Reynolds, 1999: 16, Plate 1, Figure 3, Plate 8, Figure 4, Figure 23, late Miocene (Hemphillian), Death Valley, California. *Hippipeda gyripeza* Sarjeant and Reynolds, 1999: 16-17, Plate 8, Figure 4, Figure 24, late Miocene (Hemphillian), Death Valley, California. *Hippipeda downsi* Remeika, 1999: 43-44, Figure 9, Pliocene (Blancan), ABDSP, San Diego County, California.

Diagnosis.- As for ichnospecies; monotypic.

Ichnospecies *Hippipeda downsi* Remeika, 1999
V6283
(Figure 12)

Hippipeda sp. cf. *Dinohippus* sp., (Pliocene horse track) Remeika et al., 1995: 90.
Hippipeda sp. cf. *Dinohippus* sp. Remeika, 1995: 24.
Hippipeda downsi Remeika, 1999: 43-44, Figure 9, 63.

Holotype.- ABDSP 1730/V6283 (Figure 12) is an undistorted manus hoofprint mold preserved on what used to be moist yet cohesive well-sorted micaceous sands and silts. Specimen remains uncollected *in situ*. A plaster cast replica (V6283A) is accessioned into the fossil vertebrate collections of the SRC.

Additional material.- Paratypes: V6270, V6271, and V6272 remain uncollected *in situ*. Plaster cast replicas V6270A, V6271A, and V6272A are accessioned into the SRC.

Etymology.- Fossil monodactyl equoid footprint impressions, specifically named to the honor and memory of vertebrate paleontologist Ted Downs, Chief Curator Emeritus, Los Angeles County Museum of Natural History, for his outstanding contributions to southern California paleontology.

Diagnosis.- Type specimen preserved in concave epirelief, of a digitigrade obligate quadruped equoid manus footprint, ovoidal to rectangular-shaped, distinguished by a single central digital pad toe (III) impression (mesaxonic). There is no evidence of lateral toe (II and IV) support impressions. Anteriorly, the pad is bordered by a strongly curved toe, white line, and hoofwall preserved in the relatively moist but compactible sands prior to hardening. The sole is well-pronounced, concaved downward to the bar which defines the posterior ends of the pad. The sole surrounds a nondescript V-shaped frog that is subtly expressed or absent. The overall shape of the manus print is, in most examples, wider than long. The prevalence, size, and morphology of the footprint impression along with others strongly suggest that equids are the responsible trackmakers. Observations of similarly-sized living domestic equid trackmakers leaving behind unshod imprints made in moist sand are nearly identical in size and morphology to V6283.

FIGURE 12. Undistorted well-preserved equoid manus hoofprint mold impression of *Hippipeda downsi* Remeika, 1999 (V6283) in clayey siltstone from Fish Creek Wash. Track horizon 1. For scale, the manus is 6.2 cm in length and 12.0 cm in width.

Dimensions.- Overall print length 6.2 cm; overall print breadth 12.0 cm.

Discussion.- Even though equid body fossils are a common constituent throughout the local vertebrate faunas, evidence of their footprints has been noticeably absent. This is problematic because the osteological record of the western Vallecito-Fish Creek Basin indicates that monodactyl equoid ichnotracks should be more common than those of llamoids, for example. ABDSP 1730 is the first and only documented equoid tracksite in the Colorado Desert at this time. The abundance of equoid ichnotracks in the stratum level seemed at first glance difficult to reconcile, originally appearing as physically induced soft-sediment deformation structures superficially resembling a ripplebedded horizon. Upon closer scrutiny, the structures were recognized as a fortuitous bedding-plane exposure of laterally-occurring, closely-spaced monodactyl ichnotracks confirming a biogenic origin for the deformation. Ichnotrack abundance is great, ranging in size from adult to juvenile, and distribution of footprints throughout this thoroughly trampled stratigraphic horizon will prove to be an untapped resource, providing significant sedimentological and paleoecological data. Adjacent beds, above and below, lack such deformation.

Locality.- Fish Creek Wash (Anza-Borrego Zone 28), Vallecito-Fish Creek Basin, approximately 30 km southwest of Ocotillo Wells, California. The exact locality, ABDSP 1730, is on file at the SRC.

Horizon.- Locally-derived fluvial sheet-flood deposit of the Ocotillo Formation. Track horizon 1.

Age.- Late Pliocene (Blancan III).

Possible affinity of the trackmaker.- The morphological attributes of the ABDSP 1730 ichnotracks suggest they belong to a single monodactyl trackmaker. Traditionally, two valid pliohippine candidates that shared synampomorphies are recognized from Anza-Borrego*:* *Dinohippus* sp., and the dolichohippine *Equus simplicidens*. The structurally primitive *Dinohippus* sp. is a monotypic taxon known primarily from the Hemphillian. However, in a revision of equids from Anza-Borrego, Downs and Miller (1994) extended its morphological/stratigraphic range to the late Blancan IV, based on diagnostic craniodental elements found below and above ABDSP 1730. With some hesitation, the relictual occurrence of *Dinohippus* sp., if appropriately diagnosed, seems satisfactory to include it as the likely candidate trackmaker. On the other hand, *Equus simplicidens* is exclusively a Blancan taxon yet due to an absence of cranial and postcranial material in the study area, its candidacy as a plausible trackmaker is difficult to make at this time.

ORDER ARTIODACTIPEDIDA Vialov, 1966
MORPHOFAMILY PECORIPEDIDAE Remeika et al., 1995

Ichnogenus *Lamaichnum* Aramayo and Manera de Bianco, 1987

Lamaichnum Aramayo and Manera de Bianco, 1987: 535-536; Sarjeant and Reynolds, 1999: 6.
Lamaichnium Sarjeant and Langston, 1994: 44-45; Remeika, 1999: 41-42.

Type ichnospecies.- *Lamaichnum guanicoe* Aramayo and Manera de Bianco, 1987: 535-536, Figures 5a, 5b, late Pleistocene (Lujanian), Argentina.

Other ichnospecies.- *Lamaichnum marcopodum* Sarjeant and Reynolds, 1999: 6-7, Plate 1, Figures 1-2, Figures 5-6, Miocene (Clarendonian), Inyo County, California. *Lamaichnum alfi* Sarjeant and Reynolds, 1999: 7-8, Plates 2-3, Figures 7-9, Miocene (Barstovian), San Bernardino County, California. *Lamaichnum etoromorphum* Sarjeant and Reynolds, 1999: 8-9, Plate 5, Figures 1-4, Figures 12-13, Miocene (Hemphillian), Death Valley, California. *Lamaichnum obliquiclavum* Sarjeant and Reynolds, 1999: 9-10, Plate 4, Figures 1-4, Figures 10-11, late Miocene (Hemphillian), Clark County, Nevada. *Lamaichnium borregoensis* Remeika, 1999: 41-42, Figures 3-5, Pliocene (Blancan), ABDSP, San Diego County, California.

Emended diagnosis (based on Sarjeant and Langston, 1994: 44; Sarjeant and Reynolds, 1999: 6).- Digitigrade obligate quadruped artiodactyl footprints of a small to moderate-size llamoid, showing the presence of digital cushions below the medial and distal phalanges. Footprints have an oval to rounded-rectangular shape, with two hooves in both manus and pes. Manus and pes of closely similar form. The medial (III) and lateral (IV) hoofprints have parallel axes that are paraxonic, with a narrow, linear interdigital crestline, the apices always directed forward. The medial and lateral hooves are mirror images in outline. Hoofprints widest near the heel, but taper only to a minor degree between the heel and the apex; heel rounded, apex rounded for forming a broad parabolic curve.

Discussion.- Aramayo and Manera de Bianco (1987) described the original generic and specific diagnosis of hoofprints of the type ichnospecies *Lamaichnum guanicoe* entirely on cloven-hoofed footprints typical of the trackmaker *Lama guanicoe* (guanaco). Hence, *Lamaichnum* is a valid ichnogenus, intended to embrace didactyl artiodactyl hoofprints and trackways made specifically by gracile llamoid trackmakers. This ichnogenus differs in its smaller size and morphology from *Megalamaichnum* Aramayo and Manera de Bianco (1987: 536-537) which embraces more robust didactyl llamoid hoofprints and trackways.

Ichnospecies *Lamaichnum borregoensis* Remeika, 1999
emend. Remeika, nov.
V4945, V4945A, V6105, V6274, V6274A, V6275, V6286, V6286A, V6287, V6287A
(Figure 13)

artiodactyl tracks Miller et al., 1982a: poster session; 1982b: unpaginated.
llama *Hemiauchenia* sp. Stout and Remeika, 1991: 9.
Pecoripeda sp. cf. *Camelops* sp. Stout and Remeika, 1991: 9; Remeika, 1995: 99.
trackways of *Camelops* White et al., 1991: 10.
Pecoripeda sp. cf. *Hemiauchenia* sp. (llama track) Remeika et al., 1995: 91.
Pecoripeda sp. cf. *Camelops* sp. (camel track) Remeika, 1995: 91.
Pecoripeda sp. cf. *Camelops huerfanensis* (cameloid footprints) Remeika, 1995: 37; Remeika, 1997b: IV-10.
Pecoripeda sp. cf. *Hemiauchenia* sp. Remeika, 1995: 24.
Pecoripeda Remeika, 1997: I-18.
Lamaichnium borregoensis Remeika, 1999: 41-42, Figures 4-5, 63.

Holotype.- ABDSP [IVCM] 866/V4945 (Figure 13) of an isolated right manus footprint preserved as natural mold impression (concave epirelief) on ripplebedded, very fine-grained micaceous claystone. Original specimen was accessioned into the IVCM. At present, its whereabouts is unknown. A plaster cast replica (V4945A) is accessioned into the fossil vertebrate collections of the SRC.

Additional material.- Paratypes: ABDSP 1745/V6105 (Figure 14), and V6275 accessioned into the fossil vertebrate collections of the SRC. Additional specimens V6274 (left

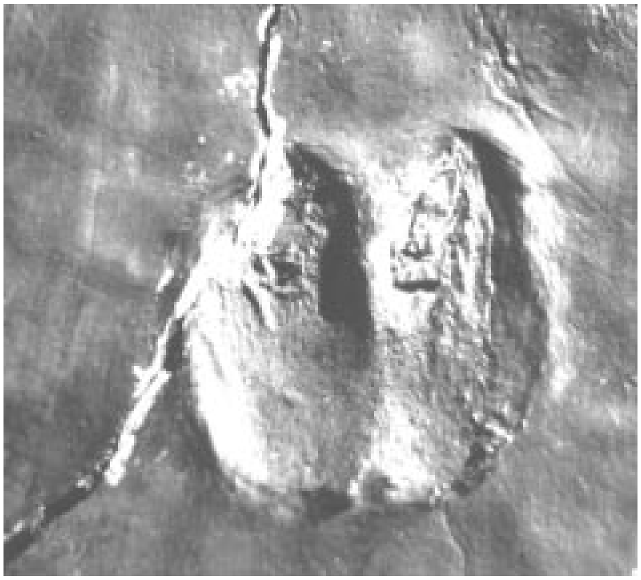


FIGURE 13. Well-preserved llamoid right manus footprint natural mold impression of *Lamaichnum borregoensis* Remeika, 1999 (V4945) in hardened claystone from Camel Ridge. Track horizon 9. The fracture to the left of the footprint impression is partially filled with a white-colored liquid plaster. For scale, the manus is 11.8 cm in length and 10.6 cm in width.

pes), V6286 (right pes), and V6287 (right manus) remain uncollected *in situ*. Plaster cast replicas (V6274A, V6286A, and V6287A) are accessioned into the SRC.

Etymology.- Named after the nearby desert hamlet of Borrego Springs, California.

Diagnosis.- Type specimen preserved in concave epirelief, represents a small to moderate-sized bidigital plantigrade to digitigrade llamoid footprint exhibiting two distinct hooves (medial III and lateral IV) in the manus. Both medial and lateral hooves are nearly identical, presenting an oval to rectangular outline longer than wide. Anteriorly, the axes of the hooves are parallel or splayed outward, separated by a linear interdigital crestline that is broadest at the front, tapering to the heel. Each hoof is broadest at the heel, which is rounded and sharply parabolic in shape. Axial surface of the hoof is flat to slightly concave, tapering mildly to a claw (toe) at the apex. Apices of hoofprint directed forward. In other specimens where manus and pes are preserved in detail, hoof apices are rounded in the manus, pointed to rounded in the pes.

Dimensions.- Holotype: (left manus): overall length 11.8 cm, greatest breadth 10.6 cm. Length of medial hoof 11.5 cm, maximum breadth 5.0 cm; length of lateral hoof 11.0 cm, maximum breadth 4.7 cm. Greatest claw tip breadth 6.2 cm.

Discussion.- The holotype of *Lamaichnum borregoensis* is not only the original specimen but best preserved of all the majority of oval-shaped didactyl footprints discovered at Camel Ridge and nearby tracksites ABDSP 1745, 1746, and 1747. Stratigraphically older (Blancan III) ichnotracks that compare favorably to the form and dimension skeletal morphology of *L. borregoensis* occur at tracksites ABDSP [IVCM] 1315, ABDSP 1726, 1728, 1729, 1731, 1734, and 1741, and remain uncollected and unnumbered *in situ*. Stratigraphically younger (Blancan IV-V) tracksites ABDSP 1748, 1749, and 1750 also yield llamoid ichnotracks in Arroyo Tapiado. These are bracketed between two prominent volcanic ash beds. The earliest known occurrence (Blancan II) of *L. borregoensis* is from the transition zone between marine-deltaic sediments of the Yuha Formation and delta-plain sediments of the Palm Spring Formation in the Fish Creek Badlands (ABDSP 1726 and ABDSP 1741), whereby footprints are preserved in concave epirelief and convex hyporelief. Locally, the footprint morphology is similar to llamoid impressions discovered in the Borrego Badlands (Beckman Wash ABDSP 1733, and Inspiration Wash ABDSP 1743) below the stratigraphic Bishop Ash datum level (Remeika and Beske-Diehl, 1996), in direct association with robust cameloid footprints of *Camelopichnum* sp. (ichnogen. nov.) and an elephantoid trackway of *Mammuthichnum* sp. (ichnogen. nov.) not previously reported from Anza-Borrego. Regionally, the footprint morphology compares favorably to llamoid impressions of *Lamaichnum obliquiclavum* (Sarjeant and Reynolds, 1999) from the Mojave Desert, California, and to *Pecoripeda* (*Ovipeda*) ichnospecies B and/or ichnospecies C (Scrivner, 1984; Scrivner and Bottjer, 1986) documented from Death Valley National Park, California. (See Nyborg and Santucci, 1999, and Santucci and Nyborg, 1999 for resource inventory).

Locality.- Camel Ridge (Anza-Borrego Zone 35), Arroyo Seco del Diablo, Vallecito-Fish Creek Basin, discovered on 9 May, 1981, approximately 34 km east of Canebrake, California. The exact locality, ABDSP [IVCM] 866, is on file at the SRC.

Horizon.- Fluvial thin-bedded, micaceous silty claystone interbed of the Ocotillo Formation. Track horizon 9.

Age.- Late Pliocene (Blancan III).

Possible affinity of the trackmaker.- *Lamaichnum borregoensis* is the most common vertebrate ichnotaxon of the Vallecito-Fish Creek Basin. Its morphologic manus and pes parameters generally fits the skeletal metacarpus and phalanges foot reconstruction model of the extinct candidate trackmaker *Hemiauchenia* sp. (Stout and Remeika, 1991). Body fossils of the fossil quadrupedal artiodactyl *Hemiauchenia macrocephala* are common in Blancan III-V (Arroyo Seco Local Fauna)-Irvingtonian I (Vallecito Creek Local Fauna) strata of the Vallecito Badlands (Remeika et al., 1995) in close proximity to Camel Ridge, and in Irvingtonian I-II (Borrego Local Fauna) strata of the Borrego Badlands (Remeika and Jefferson, 1993). Size and footprint morphology clearly suggests it was produced by a llama using a quadrupedal gait and does not vary significantly from extant llama (*Lama glama*) footprint impressions (Table 3).

TABLE 3. Measurements of manus and pes hoof impressions of *Lamaichnum borregoensis* [1-6] compared with modern llama footprint examples of *Lama glama* collected from Borrego Valley, California [7], and from the Oak Valley Llama Ranch in Ramona, California [8]. ICN, ichnite; RM, right manus; LM, left manus; RP, right pes; LP, left pes; PL, print length; PB, print breadth; MHL, medial hoof length; MHB, medial hoof breadth; LHL, lateral hoof length; LHB, lateral hoof breadth; CTB, claw tip breadth; IND, indetermined. Measurements in centimeters (cm).

IND	PL	PB	MHL	MHB	LHL	LHB	CTB
ABDSP [IVCM] 866/V4945							
RM 1	11.8	10.6	11.5	5.0	11.0	4.7	6.2
ABDSP [IVCM] 866/V6105							
RM 2	11.6	9.7	11.6	5.2	9.5	4.2	3.0
ABDSP [IVCM] 866/V6274							
LP 3	12.5	9.0	12.5	4.9	11.2	4.0	7.1
ABDSP [IVCM] 866/V6275							
RM 4	IND	9.0	IND	4.3	IND	3.9	3.7
ABDSP [IVCM] 866/V6286							
RP 5	10.0	8.3	9.9	3.6	10.0	3.3	4.9
ABDSP [IVCM] 866/V6287							
RM 6	10.5	7.9	10.5	3.1	10.6	3.0	2.5
Lama glama							
RM 7	10.2	8.3	10.2	3.5	10.1	3.3	5.1
RM 8	11.2	7.9	10.7	3.5	11.2	3.2	5.5
RP 8	10.4	6.8	10.2	3.0	10.4	3.0	3.5
LM 8	11.7	7.9	11.2	3.5	11.7	3.7	6.0
LP 8	10.4	8.0	10.4	3.0	10.3	3.3	6.0

Ichnogenus *Megalamaichnum* Aramayo and Manera de Bianco, 1987

Megalamaichnum Aramayo and Manera de Bianco, 1987: 536-537.

Type ichnospecies.- *Megalamaichnum tulipensis* Aramayo and Manera de Bianco, 1987: 536-537, 545 Figures 6a, 6b; Aramayo and Manera de Bianco, 1996: 50-51, 51 Plate 2a, 2b, 55 Figure 4.

Emended diagnosis (based on Aramayo and Manera de Bianco, 1987: 537; 1996: 50).- Digitigrade obligate quadruped artiodactyl footprints of a moderate to large-size llamoid, showing the presence of digital cushions below the medial and distal phalanges. Footprints have an oval to rounded-rectangular shape, with two hooves in both manus and pes. Manus and pes of closely similar form. The medial (III) and lateral (IV) hoofprints have parallel axes that are paraxonic, with a narrow linear interdigital crestline, the apices always directed forward. The medial and lateral hooves are mirror images in outline. Hoofprints widest near the heel, and taper to each apex; heel rounded forming a broad parabolic curve. This ichnogenus differs in its larger size and morphology from the smaller version *Lamaichnum*.

Discussion.- Aramayo and Manera de Bianco (1987, 1996) described the original generic and specific diagnosis of hoofprints of the type ichnospecies *Megalamaichnum tulipensis* entirely on large cloven-hoofed fossil footprints. Hence, *Megalamaichnum* is a credible ichnogenus, intended to embrace didactyl artiodactyl hoofprints and trackways made specifically by robust llamoid trackmakers, and not intended to include gracile llamoid ichnotracks typically represented by the ichnogenus *Lamaichnum*.

Ichnospecies *Megalamaichnum albus* ichnosp. nov. V6288, V6289, V6290, V6291 (Figure 15)

fossil trackways of camelids Stout et al., 1987: 4.
Megatylopus Stout and Remeika, 1991: 9.
Megatylopus footprints, trackways White et al., 1991: 10.
Hemphillian-Blancan camel *Megatylopus* Stout and Remeika, 1991: 9.
Blancan camelopine *Camelops* Stout and Remeika, 1991: 9.
Pecoripeda sp. cf. *Megatylopus* sp. (large camel track) Remeika, 1995: 91.
Pecoripeda sp. cf. *Megatylopus* sp. Remeika, 1995: 24.
Megatylopus sp. cf. *Blancocamelus* sp. Remeika, 1995: 24.
Pecoripeda sp. cf. *Blancocamelus* sp. (camel track) Remeika et al., 1995: 90.
Ichnogenus *Gambapes*? (large artiodactyl) Remeika, 1999: 37, 41, 63.

Holotype.- ABDSP 1726/V6288 (Figure 15) of an isolated right manus footprint preserved as a natural ceiling cast impression (convex hyporelief) on a panel of marginal-marine foreshore claystone. The panel is part of a rockfall that collapsed during the 1968 M6.5 Borrego Mountain Earthquake. Original specimen remains uncollected *in situ*.

Additional material.- Paratypes: ABDSP 1745/V6289 (manus ceiling cast) and V6290 (pes floor mold) are isolated footprint impressions accessioned into the vertebrate collections of the SRC. An additional specimen ABDSP 1728/V6291 remains

FIGURE 14. Photograph of a set of llamoid tracks (*Lamaichnum borregoensis*) preserved as a natural mold impression in hardened claystone from Camel Ridge. Track horizon 9. Scale: same as used in Figure 13.

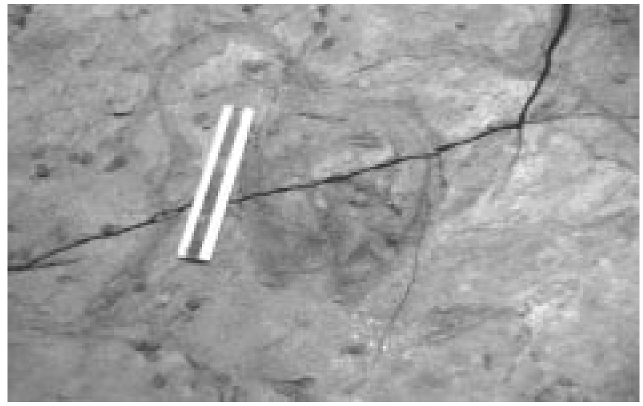


FIGURE 15. Large llamoid track of *Megalamaichnum albus* (ichnosp. nov.) (V6288) preserved as a ceiling cast in marine-deltaic claystone in Hanging Tracks Wash. Ruler for scale (15 cm). The right manus measures 18.5 cm in length and 14.5 cm in width.

unmeasured due to the nature of outcrop, and uncollected *in situ*.

Etymology.- Latin, *albus* = white. The specific epithet is in recognition of Dr. John A. White, for his numerous and significant contributions to ABDSP's vertebrate paleontology record and the systematics and anatomy of the Leporidae. John White accompanied me into Fish Creek Canyon prior to our scheduled field trip for the 1991 Society of Vertebrate Paleontology meetings when I made one of the *Megalamaichnum albus* tracksite discoveries.

Diagnosis.- As for ichnogenus.

Dimensions.- Holotype: (right manus): overall length 18.5 cm, greatest breadth 14.5 cm. Length of medial hoof 18.5 cm, maximum breadth 7.0 cm; length of lateral hoof 18.5 cm, maximum breadth 7.0 cm. Greatest claw tip breadth 3.0 cm.

Discussion.- The footprint morphology resembles the large llamoid impression *Lamaichnum macropodum* of Sarjeant and Reynolds (1999) from the Mojave Desert, and *Pecoripeda* (*Ovipeda*) ichnospecies A of Scrivner (1984), and Scrivner and Bottjer (1986) from Death Valley National Park, California. (See Nyborg and Santucci, 1999; Santucci and Nyborg, 1999 for resource inventory).

Locality.- Hanging Tracks Wash (Anza-Borrego Zone 7), North Fork of Fish Creek Wash, Vallecito-Fish Creek Basin, approximately 28 km south of Ocotillo Wells, California. The exact locality, ABDSP 1726, is on file at the SRC.

Horizon.- Finely-interstratified silty claystones of the marginal-marine Yuha Formation. The footprint horizon is bracketed between epifaunal shellhash deposits of *Turritella imperialis*, and an oyster-anomiid coquina dominated by *Dendostrea vespertina.*

Age.- Holotype: early Pliocene (Blancan II). Paratypes: V6289, V6290, and V6291, late Pliocene (Blancan III).

Possible affinity of the trackmaker.- The Blancan-Irvingtonian body-fossil record in the study area includes half-a-dozen artiodactyl taxa, including *Blancocamelus* sp., *Camelops* sp., *Hemiauchenia blancoensis*, *H. macrocephala*, *Megatylopus* sp., and *Titanotylopus* sp. (Remeika et al., 1995). Only the extinct llama *Hemiauchenia blancoensis* is well-represented, with skeletal remains common through the vertical-continuous section. This llama is larger than the gracile *H. macrocephala.* Based on a morphometric analysis of the available sample of ichnotracks, a reasonable assignment to the candidate trackmaker *H. blancoensis* seems appropriate. At the present time, no cameloid footprint impressions occur in the study area thus ruling out camelopines as the likely trackmakers.

ORDER PROBOSCIDIPEDIDA Remeika et al., 1995
MORPHOFAMILY GOMPHOTHERIIPEDIDAE
ichnofam. nov.

Ichnogenus Stegomastodonichnum Aramayo and Manera de Bianco, 1987

Stegomastodonichnum Aramayo and Manera de Bianco, 1987: 521-522, 531 Figures 7a, 7b, 7c.

Type ichnospecies. – *Stegomastodonichnum australis* Aramayo and Manera de Bianco, 1987: 521-522, 531 Figures 7a, 7b, 7c.

Diagnosis. – The morphofamily Gomphotheriipedidae is distinguished by the presence of large, deeply-impressed plantigrade obligate quadruped footprints. The robusticity of the type specimen is large enough to have been made by a pentadactyl gomphotherioid trackmaker. Footprint is preserved in convex hyporelief, featuring a broad oblong to oval-shaped impression, apex forward, with three pronounced digits (II-IV) oriented anteriorly at the terminus. The exhibition of a tridactyl functional morphology is consistent with the predicted anatomy of extant elephantoid pes footprint impressions and is not unusual. Digital pads II-IV are equal in size and character, and nearly parallel in orientation. Digits are robust and short, with a blunt anterior, and semi-circular in shape as suggested by imprint outline. Lateral digits I and V are indistinct or effaced, reduced as the circumference of the depression shrank when the foot was withdrawn. No claw marks present. The metatarsal pad is broad, flat, with a rounded heel along the posterior margin. The metatarsal pad is about 2.5 cm thick. The depth of imprint is 13.5 cm.

Ichnospecies *Stegomastodonichnum garbanii* ichnosp. nov.
V6292
(Figure 16)

indeterminate gomphotheroid (ichnogenus *Thrinaxopus* ?) Remeika, 1999: 37, 38, 63.

Holotype. – ABDSP 1732/V6292 right pes (Figure 16) footprint impression preserved as an undistorted although somewhat featureless ichnotrack on the underside of a massive channel sandstone strike ridge panel alongside ichnotracks of *Chelipus therates* (Figure 17). The pes impression remains uncollected *in situ*.

Additional material.- Elephantoid footprint impressions that compare favorably to V6292 have not been found.

Etymology. – The specific designation of the ichnospecies is named in recognition of vertebrate paleontologist Harley J. Garbani, and his wife Mary, honoring their support of paleontology in ABDSP spanning five decades.

Diagnosis. – As for ichnogenus.

Dimensions. – Holotype: right pes (V6292): overall print length 37.5 cm; overall print breadth 27.5 cm. Length of digits: I, indeterminate; II, 5.5 cm; III, 7.5 cm; IV, 2.5 cm; V, indeterminate. Breadth of digits: I, indeterminate; II, 7.5 cm; III, 8.4 cm; IV, 5.0 cm; V, indeterminate.

FIGURE 16. Well-preserved elephantoid ceiling cast impression of *Stegomastodonichnum garbanii* (ichnosp. nov.) (V6292) in sandstone from Fish Creek Canyon. Track horizon 4. Posterior oblique view. For scale, the footprint measures 37.5 cm in length and 27.5 cm in width.

FIGURE 17. Posterior oblique view of the ABDSP 1732 ceiling panel. Track horizon 4. Note set of canoid tracks of *Chelipus therates* (V6276 and V6277) with the inferred trackway overprinted by the large elephantoid track of S*tegomastodonichnum garbanii* (V6292). Also note presence of an isolated, paretially-preserved feloid track of *Pumaeichnum milleri* (unnumbered *in situ*) to the left of the canoid impressions. Scale: same as used in Figures 7 and 16.

Locality. – Fish Creek Canyon (Anza-Borrego Zone 29), Vallecito-Fish Creek Basin, approximately 29 km southwest of Ocotillo Wells, California. The exact locality, ABDSP 1732, is on file at the SRC.

Horizon. – Thick-bedded, fine-grained fluvio-deltaic arenite deposit of the Palm Spring Formation. Track horizon 4.

Age. – Late Pliocene (Blancan III).

Possible affinity of the trackmaker. – Although it is not possible to ascertain the identity of the trackmaker with certainty, the attributes of the isolated ABDSP 1732 track suggests it was made by an elephantid. Possible candidates that were large enough include: *Stegomastodon mirificus, Cuvieronius* sp., and *Mammut americanum*. It is possible one of these is the responsible trackmaker. The stegomastodont *Stegomastodon* sp., and gomphothere *Cuvieronius* sp., are primarily Blancan taxa; both are reported from the Vallecito

Badlands (Remeika et al., 1995). Specifically, *S. mirificus* has been recovered from the late Blancan Verde Formation of central Arizona (Agenbroad et al., 1998). The mastodont *M. americanum* ranges from Blancan to Rancholabrean in age, may occur in the Vallecito Badlands (Remeika et al., 1995), and has recently been recovered in late Pleistocene sediments in Diamond Valley, Riverside County, California (Springer et al., 1999).

CONCLUSIONS

The Fish Creek Canyon Ichnofauna is a ubiquitous avian and mammaloid hoof- and footprint vertebrate assemblage recognized from the Vallecito-Fish Creek Basin. Seven morphofamilies are recognized, represented by nine ichnospecies, making it one of the most varied ichnofaunas yet discovered in the Colorado Desert. Indeed, only the ichnofauna described from the Hemphillian of Death Valley by Scrivner and Bottjer (1986) shows a comparable diversity of morphotypes.

The vertebrate ichnofauna includes:

- small ansiodactyl bird footprints and trackways of *Gruipeda diabloensis* that closely resemble, in size and morphology, tracks made by the modern calidridine least sandpiper *Calidris minutilla*, herein assigned to the emended ichnogenus *Gruipeda* (Remeika, 1999).
- a new aquatic musteloid, *Mustelidichnum vallecitoensis*, is interpreted to be the first unequivocal footprint evidence of an extinct river otter reported from the Pliocene of California.
- footprints of a typical carnivorian canoid, *Chelipus therates*, are interpreted to be identical in size and morphological parameters to modern-day footprints made by coyote-sized canids.
- intermediate-sized feloid footprint impressions of *Pumaeichnum milleri* are interpreted to be morphometrically divided between the genera *Lynx* and *Felis* yet exclusively share a close resemblance to lynxes and pumas.
- a robust footprint impression of a right manus representing the puma-sized feloid *Pumaeichnum stouti* (new) exhibits claw tips directly joined to the anterior end of each digital pad. This is interpreted to be the first recognized occurrence of an extinct cheetah footprint and the earliest record of cheetah in the Pliocene of California.
- abundant fossil monodactyl equoid footprint impressions are assigned the name *Hippipeda downsi*. Based on diagnostic craniodental elements belonging to the equid *Dinohippus* sp. found below and above the tracksite, the impressions are interpreted to be from this likely candidate trackmaker.
- abundant gracile artiodactyl footprints and trackways of *Lamaichnum borregoensis* occur throughout the stratigraphic section. The morphologic manus and pes parameters generally fit the skeletal metacarpus and phalanges foot reconstruction model of the extinct candidate trackmaker *Hemiauchenia macrocephala*, body fossils of which are a common constituent of the Arroyo Seco Local Fauna in the study area (Remeika et al., 1995).
- abundant robust artiodactyl footprints and trackways of *Megalamaichnum albus* (new) clearly indicate a larger llamoid ichnospecies was common throughout the vertical-continuous stratigraphic section. Based on morphometric analysis, *Hemiauchenia blancoensis* is the reasonable candidate trackmaker, body fossils of which are also a common constituent of the Arroyo Seco Local Fauna (Remeika et al., 1995). The most common trackmakers were the llamoids, with *Lamaichnum borregoensis* ranking first and *Megalamaichnum albus* ranking second in relative abundance.
- the presence of a large, deeply-impressed footprint suggests it was made by an elephantid. Possible candidates include *Stegomastodon mirificus*, *Cuvieronius* sp., and *Mammut americanum*. The impression is the first recognized gomphotherioid footprint discovered in the Colorado Desert and is assigned to the new ichnospecies *Stegomastodonichnum garbanii*. It occurs in direct association with feloid, canoid, and llamoid tracks.

The presence and abundance of tracks throughout multiple stratigraphic levels is noteworthy, and indicates the area was frequented by a mammalian megafauna for a prolonged period of time, ranging from Blancan II-V. The abundant and well-preserved footprints occur in basin-margin strata of a vertical-continuous mixed-affinity marine-deltaic, delta-plain, and fluvial-alluvial fan depositional environments. Each stratum is a rich source of mammalian-dominated ichnocoenoses. The clarity of footprint preservation is extraordinary, preserved as positive ceiling casts on the undersides of thick, overhanging sandstone ledges, or as negative floor impressions associated with various interstratified, dessication mud drapes. The majority of trackmakers are hitherto unknown from the osteological record of the study area but are represented in the late Blancan V to early Irvingtonian I megafauna of the Vallecito Badlands (Remeika et al., 1995).

ACKNOWLEDGMENTS

I am grateful to Silvia A. Aramayo, of the Departamento de Geologia, Universidad Nac. Del Sur, Argentina, and Torrey G. Nyborg, of the Department of Geology, Kent State University, Ohio, for providing information about fossil vertebrate tracksites at their respective research localities: Aramayo, Provincia de Buenos Aires, Argentina; and Nyborg, Death Valley National Park, California. I thank District Interpretive Specialist Brian W. Cahill for his assistance and thoroughness with scanning the footprint illustrations, and Research Analyst I (Geographic Information Systems) P. I. Lydia Louise Jee who skillfully prepared the production Figures 3-17 published herein, and offered suggestions that improved the final version of the manuscript substantially. I am also indebted to State Park Ranger I Chris H. Smith for supplying the photograph for Figure 17, and to District Archeologist George T. Jefferson for assigning me with specimen numbers, and for kindly granting access to collections in his care. Unless noted, all ichnites were discovered, collected, and photographed by the author.

REFERENCES

Agenbroad, L.D., D.P. Hallman, and C.N. Jass, 1998. Description and comparative morphometrics of a *Stegomastodon mirificus* from the Verde Formation, Yavapi County, Arizona. Abstracts with Programs. Journal of Vertebrate Paleontology 18 (3): 23A.

Aramayo, S.A., and T. Manera de Bianco, 1987. Hallazgo de una icnofauna continental (Pleistoceno tardío) en la localidad de Pehuen-Co (partido de Coronel Rosales), Provincia de Buenos Aires, Argentina. Pt. 1, Edentata, Litopterna, Proboscidea. Pt. 2, Carnivora, Artiodactyla y Aves. *In* IV Congr. Latinoam. Paleontol. (Bolivia), 1: 516-31, 532-47.

_____, 1996. Edad y nuevos hallazgos de icnitas de mamiferos y aves en el yacimiento paleoicnológico de Pehuen-Co (Pleistoceno tardío), Provincia de Buenos Aires, Argentina. Asociación Paleontológica Argentina. Publicación Especìal 4, 1st Reunión Argentina de Icnología: 47-57.

Buchheim, H.P., V.L. Leggitt, R.E. Biaggi, and M.A. Loewen, 1999. Paleoenvironments of avian trackway sites within the "Olla member", Palm Spring Formation, Anza-Borrego Desert State Park. San Bernardino County Museum Association Quarterly 46 (2): 47-52, 57.

Cande, S.C., and D.V. Kent, 1995. Revised calibration of the geomagnetic polarity time scale for the late Cretaceous and Cenozoic. Journal of Geophysical Research 100: 6093-6095.

Cunningham, G.D., 1984. The Plio-Pleistocene Dipodomyinae and geology of the Palm Spring Formation, Anza-Borrego Desert, California. Master of Science Thesis, Idaho State University, Pocatello. 193 p.

Downs, T., and J.A. White, 1968. A vertebrate faunal succession in superposed sediments from late Pliocene to middle Pleistocene in California. *In* Tertiary/Quaternary Boundary, International Geological Congress 23, Prague 10: 41-47.

Downs, T., and G.J. Miller, 1994. Late Cenozoic equids from Anza-Borrego Desert, California. Natural History Museum of Los Angeles County Contributions in Science 440:1-90.

Dibblee, T.W., Jr., 1954. Geology of the Imperial Valley region, California. *In* Geology of Southern California, edited by R.H. Jahns. California Division of Mines and Geology Bulletin 170 (2, 2): 21-81.

Jefferson, G.T., and A. Tejada-Flores, 1995. Late Blancan *Acinonyx* (Carnivora, Felidae) from the Vallecito Creek Local Fauna of Anza-Borrego Desert State Park, California. San Bernardino County Museum Quarterly 42 (2): 33.

Johnson, N.M., C.B. Officer, N.D. Opdyke, G.D. Woodard, P.K. Zeitler, and E.H. Lindsay, 1983. Rates of late Cenozoic tectonism in the Vallecito-Fish Creek Basin, western Imperial County, California. Geology 11: 664-667.

Kurtén, B., and E. Anderson, 1980. Pleistocene mammals of North America. Columbia University Press, New York. 442 p.

Leonardi, G., 1987. Glossary and manual of tetrapod footprint palaeoichnology República Federativa do Brasil ministério das minas e energia departmento nacional da producäo mineral: 1-117.

Miller, G.J., B.W. Stout, and P. Remeika, 1982a. Irvingtonian ichnites from the Anza-Borrego Desert, California. Society of Vertebrate Paleontology. Abstracts with Programs. 42nd Annual Meeting, Mexico City. Poster session.

_____, 1982b. A preliminary report on mid-Blancan vertebrate ichnites from the Anza-Borrego Desert. Abstracts with Programs. Western Association of Vertebrate Paleontologists, San Diego, California. Unpaginated.

Nyborg, T.G., and V.L. Santucci, 1999. The Death Valley National Park paleontology survey. National Park Service, Geological Resources Technical Report, NPS/NRGRD/GRDTR-99/01: 1-66.

Opdyke, N.D., E.H. Lindsay, N.M. Johnson, and T. Downs, 1977. The paleomagnetism and magnetic polarity stratigraphy of the mammal-bearing section of Anza-Borrego State Park, California. Quaternary Research 7: 316-329.

Panin, N., and E. Avram, 1962. Noe urme de vertebrate in Miocenul Subcarpatilor Ruminesti. Studii Cercet. Geology 7: 455-84.

Remeika, P., 1992. Preliminary report on the stratigraphy and vertebrate fauna of the middle Pleistocene Ocotillo Formation, Borrego Badlands, Anza-Borrego Desert State Park, California. San Bernardino County Museum Association Quarterly 39 (2): 25-26.

_____, 1993. Megafossil mammalian trackways from Anza-Borrego. Abstracts with Programs. Western Association of Vertebrate Paleontologists. San Bernardino County Museum, Redlands, California. Unpaginated.

_____, 1994. Lower Pliocene angiosperm hardwoods from the Vallecito-Fish Creek Basin, Anza-Borrego Desert State Park, California: deltaic stratigraphy, paleoclimate, paleoenvironment, and phytogeographic significance. San Bernardino County Museum Association Quarterly 41 (3): 26-27.

_____, 1995. Basin tectonics, stratigraphy, and depositional environments of the western Salton Trough detachment. *In* Paleontology and Geology of the Western Salton Trough Detachment, Anza-Borrego Desert State Park, California, edited by P. Remeika, and A. Sturz. San Diego Association of Geologists Field Trip Guidebook I: 3-54.

_____, 1997. The Neogene Vallecito-Fish Creek Basin: tilt-block/half-graben extension, stratigraphy, and paleontology. *In* Geology and Paleontology of the Anza-Borrego Region, California, edited by P. Deen, C. Metzler, and A. Trujillo. National Association of Geoscience Teachers Spring Field Conference Guidebook: I-1 – I-32.

_____, 1998a. Marine invertebrate paleontology and stratigraphy of the Vallecito-Fish Creek Basin: a historic review, synthesis and revision. *In* Geology and Geothermal Resources of the Imperial and Mexicali Valleys, edited by L. Lindsay, and W.G. Hample. San Diego Association of Geologists Field Trip Guidebook: 59-92.

_____, 1998b. Interdisciplinary age control of the western Borrego Badlands, Anza-Borrego Desert State Park, California. Abstracts with Programs. The 5th Conference on Fossil Resources, Rapid City, South Dakota: S18.

_____, 1999. Identification, stratigraphy, and age of Neogene vertebrate footprints from the Vallecito-Fish Creek Basin, Anza-Borrego Desert State Park, California. San Bernardino County Museum Association Quarterly 46 (2): 37-45, 63.

Remeika, P., and S. Beske-Diehl, 1996. Magnetostratigraphy of the western Borrego Badlands, Anza-Borrego Desert State Park, California: implications for stratigraphic age control. *In* Sturzstroms and Detachment Faults, Anza-Borrego Desert State Park, California, edited by P.L. Abbott, and D.C. Seymour. South Coast Geological Society Annual Field Trip Guidebook 24: 209-220.

Remeika, P., I.W. Fischbein, and S.A. Fischbein, 1988. Lower Pliocene petrified wood from the Palm Spring Formation, Anza-Borrego Desert State Park, California. Review of Palaeobotany and Palynology 56: 183-198.

Remeika, P., and G.T. Jefferson, 1993. The Borrego Local Fauna: revised basin-margin stratigraphy and paleontology of the western Borrego Badlands, Anza-Borrego Desert State Park, California. *In* Ashes, Faults and Basin, edited by R.E. Reynolds and J. Reynolds. San Bernardino County Museum Association Special Publication 93-1: 90-93.

Remeika, P., G.T. Jefferson, and L.K. Murray, 1995. Fossil vertebrate faunal list for the Vallecito-Fish Creek and Borrego-San Felipe Basins, Anza-Borrego Desert State Park and vicinity, California. *In* Paleontology and Geology of the Western Salton Trough Detachment, Anza-Borrego Desert State Park, California, edited by P. Remeika, and A. Sturz. San Diego Association of Geologists Field Trip Guidebook I: 82-93.

Remeika, P., and L. Lindsay, 1992. Geology of Anza-Borrego: Edge of Creation. Sunbelt Publications, Kendall/Hunt Publishing Company, Dubuque, Iowa. 208 p.

Repenning, C.A., 1987. Biochronology of the microtine rodents of the United States. *In* Cenozoic Mammals of North America: Geochronology and Biostratigraphy, edited by M.O. Woodburne. University of California Press, Berkeley: 236-268.

Santucci, V.L. and T.G. Nyborg, 1999. Paleontological resource management, systematic recording, and preservation of vertebrate tracks within Death Valley National Park. San Bernardino County Museum Association Quarterly 46 (2): 21-26.

Sarjeant, W.A.S., and W. Langston, Jr., 1994. Vertebrate footprints and invertebrate traces from the Chardonian (late Eocene) of Trans-Pecos, Texas. Texas Memorial Museum Bulletin 36: 1-86.

Savage, D.E., 1960. A survey of various late Cenozoic vertebrate faunas of the panhandle of Texas. Part III. University of California Publication of Geological Sciences 36: 317-344.

Scrivner, P.J., 1984. Stratigraphy, sedimentology and vertebrate ichnology of the Copper Canyon Formation (Neogene), Death Valley National Monument. Master of Science Thesis, University of California, Los Angeles. 334 p.

Scrivner, P.J. and D.J. Bottjer, 1986. Neogene avian and mammalian tracks from Death Valley National Monument, California; their context, classification and preservation. Palaeogeography, Palaeoclimatology, Palaeoecology 57: 285-331.

Springer, K., E. Scott, C.J. Sagebiel, and K.M. Scott, 1999. A late Pleistocene lake-edge vertebrate assemblage from the Diamond Valley, Riverside County, California. Abstracts with Programs. Journal of Vertebrate Paleontology 19 (3): 77A.

Stout, B.W., G.J. Miller, and P. Remeika, 1987. Neogene mega-vertebrate ichnites from the Vallecito Basin, Anza-Borrego Desert State Park, California. Desert Protective Council Educational Bulletin 87-1Sp: 5.

Stout, B.W. and P. Remeika, 1991. Status report on three major camelid tracksites in the lower Pliocene delta sequence, Vallecito-Fish Creek Basin, Anza-Borrego Desert State Park. Symposium on the Scientific Value of the Desert. Anza-Borrego Foundation, Borrego Springs, California: 9.

Vialov, O.S., 1965. Stratigrafiya neogenovix molass Predcarpatskogo progiba. Kiev. Naukova Dumka, pt. K.

_____, 1966. Sledy zhiznedeiatel'nosti organizmow I ikh paleontogicheskoe znachenie. Kiev: Naukova Dumka. 219 p.

Werdelin, L., 1985. Small Pleistocene felines of North America. Journal of Vertebrate Paleontology 5 (3): 194-210.

White, J.A., E.H. Lindsay, P. Remeika, B.W. Stout, T. Downs, and M. Cassiliano, 1991. Society of Vertebrate Paleontology Field Trip Guide to the Anza-Borrego Desert. Society of Vertebrate Paleontology, Annual Meeting Guidebook: 1-23.

Woodring, W.P., 1931. Distribution and age of the marine Tertiary deposits of the Colorado Desert. Carnegie Institute of Washington Publication 418: 1-25.

A CRANIODENTAL INTERPRETATION OF THE DIETARY HABITS OF *POEBROTHERIUM WILSONI* (CAMELIDAE) FROM THE OLIGOCENE OF BADLANDS NATIONAL PARK, SOUTH DAKOTA

WILLIAM P. WALL AND JACQUELINE M. HAUPTMAN
Dept. of Biology, Georgia College & State University, Milledgeville, GA 31061

ABSTRACT— The craniodental morphology of the Oligocene camelid, *Poebrotherium wilsoni* was analyzed in an effort to determine the likely dietary habits of this species. Craniodental indices shown to correlate with dietary habits were applied to modern species of known dietary habits (browser, mixed feeder and grazer) and compared to *Poebrotherium wilsoni.* Hypsodonty index, relative muzzle width and relative length of the upper premolar row were utilized for all groups. Tooth wear was examined qualitatively and similar comparisons were made. *Camelus dromedarius* was separately subjected to the same analysis, and compared to *Poebrotherium wilsoni* to address differences in the two forms. The comparisons revealed that *Poebrotherium wilsoni* was not a grazer. It was more similar to the browsers and mixed feeders in hypsodonty, length of premolar row, and tooth topography and wear. Relative muzzle width was the only index in which *Poebrotherium wilsoni* was similar to the grazers. Locality data from the literature and our fieldwork suggests that *Poebrotherium wilsoni* ranged over a variety of habitats, further substantiating the probability of broad dietary preferences in this early camelid. *Camelus dromedarius,* a mixed feeder, was significantly different from *Poebrotherium wilsoni* in all indices.

INTRODUCTION

Camelid dentition is primitive among living selenodont artiodactyls in the retention of upper lateral incisors and three premolars. The three-chambered ruminating stomach found in camelids is also less efficient than that of the true ruminants with their four-chambered stomachs. The refugial distribution (Africa and South America) and specialized habitats (deserts and high mountains) of modern camelids is probably the result of their inability to compete effectively with advanced ruminants (Wheeler, 1995). The fossil record of camelids indicates that they had a much broader geographic range for most of their history. Modern camelids have proportionally long limbs, digitigrade feet, and a pacing gait that makes them efficient travelers in open terrain. The locomotor abilities of camelids therefore appear to be at least comparable to those of most ruminants. A possible cause for the inability of camelids to compete effectively with ruminants is lower efficiency at food processing. It is commonly believed that the development of the ruminant stomach was responsible for the decline of non-ruminant large herbivores. However, MacFadden (1992) does not believe this factor alone was responsible for the decline in diversity of horses. If that is true, then the history of camelids may be more complicated as well.

Poebrotherium wilsoni (Figure 1) from the Orellan of North America is the most well known early camelid, and a member of the central stock from which modern camels and llamas have evolved. Skeletal remains indicate *P. wilsoni* was a lightly built artiodactyl measuring approximately 75 cm in height. It was unique among its contemporaries in having a long slender neck and limbs that were well suited for efficient running. The dental characteristics of *Poebrotherium* are primitive for the family Camelidae.

The purpose of this paper is to describe the likely dietary habits *of Poebrotherium wilsoni* in order to better understand the selection pressures acting early in camelid evolution.

CAMELID SYSTEMATICS

Camelids (suborder Tylopoda) underwent nearly forty million years of evolution in North America (McKenna, 1966; Schultz, 1959; Scott, 1929, 1940; Wilson, 1974; Wortman, 1898). During the Plio-Pleistocene (3 MYBP), some species of the llama-like genus *Hemiauchenia* migrated to South America via the Panamanian Land Bridge and gave rise to *Llama and Vicugna* about 2 MYBP (Webb; 1965, 1972, 1974). Contemporaneously, other species, possibly in the genus *Paracamelus,* migrated from North America to Eurasia via the Beringia Land Bridge ultimately giving rise to the two Old World camels, *Camelus dromedarius and C.*

bactrianus (Gauthier-Pilthers and Dagg, 1981). Camels became extinct in North America as recently as 10,000-12,000 years ago with *Camelops* surviving well into the Pleistocene (Harrison, 1985; Schultz, 1959; Webb, 1965, 1972, 1974).

Poebrotherium has long been recognized as an early member of the central stock from which modern camels and llamas evolved, however, not all authors agree on the ancestor of *Poebrotherium* (see for example, Gazin, 1955; Scott, 1940; Wilson, 1974). The poor fossil record of camelids prior to *Poebrotherium* complicates the situation. Wortman (1898) placed the Uintan artiodactyl, *Protylopus petersoni,* directly ancestral to *Poebrotherium.* Gazin (1955), however, believed *Poebrodon kayi*, also from the Uintan, was the direct ancestor to *Poebrotherium*. Gazin placed *Protylopus* in the family Oromerycidae. Wilson (1974) in his description of a new species of *Poebrotherium, P. franki,* from the Chadronian stated that *P. franki* was more closely related to *Protylopus* than to *Poebrodon.* The most recent systematic revision of camelids (Honey et al. 1998) questions the placement of *P. franki* in the genus *Poebrotherium*, regards *Poebrodon* to be the most primitive camelid, and places *Poebrotherium* as the sister taxon to all higher camelids.

Four species of Orellan *Poebrotherium* have been named (Scott, 1940): *P. wilsoni,* Leidy, 1847, lower Brule; *P. labiatum,* Cope, 1881, lower Brule; *P. andersoni,* Troxell, 1917, lower Brule; and *P. eximium,* Hay, 1902, base of the lower Brule. Loomis (1928) considered the size disparity and the difference in the anterior dentition between *Poebrotherium labiatum and P. wilsoni* as sexual differences. He synonymized *P. labiatum* and *P. andersoni* with *P. wilsoni.* Loomis accepted *P. eximium as* a distinct species because it lacks the diastema between the canine and premolar teeth characteristic of *P. wilsoni*.

Scott (1940) agreed with Loomis' assessment that *P. andersoni* was not a valid species. However, he questioned Loomis' (1928) failure to separate *P. wilsoni and* P. *labiatum* in light of the striking skeletal differences between the two species.

Prothero (1996) recognized *P. wilsoni*, *P. eximium*, *P. franki*, and he named a new species, *P. chadronense.* All of the specimens used in this study (from the Orellan of Badlands National Park) are *P. wilsoni*.

McKenna (1966) and Webb (1972) recognized four genera of late Oligocene camelids; *Pseudolabis* with no known descendants*, Paratylopus* the ancestral long-necked camelid*, Dyseotylopus* the basal representative of the modern camelids*,* and an unknown ancestor to the stenomyline camels. Prothero (1996) showed that *Dyseotylopus* is a junior synonym of *Miotylopus*.

MATERIALS AND METHODS

Data were collected on both fossil and modern specimens. The fossil specimens are housed in the Georgia College & State University Vertebrate Paleontology collection (GCVP); and the modern specimens are housed in the Georgia College & State University Mammal collection (GCM) or the University of Nebraska State Museum (UNSM). The specimens measured are listed in Appendix 1. All measurements were taken with Mitutoyo calipers with 0.05 mm accuracy. The mean values for each measurement were used to calculate each craniodental index. Significant differences in mean values were determined by implementing a *t-test* *($p<0.05$).*

Dietary information was collected from the literature (Janis, 1988; Janis and Ehrhardt, 1988; Nowak, 1991; Solounias and Dawson-Saunders, 1988; Solounias et al., 1988). Specifically, Estes (1972) was used for the dietary information for *Gazella granti.* Grazers feed primarily on *grasses* (> 90% of diet is grass); browsers feed primarily on fruit, leaves and young *shoots (*<10% of diet is *grass);* mixed feeders feed on a variety of material (10-90% of diet is grass*).* Mixed feeders may vary their feeding seasonally or they may select different habitats throughout the year. The modern specimens were grouped into their respective feeding categories: browsers*,* mixed feeders and grazers based on dietary descriptions in the literature.

The following craniodental indices were employed: relative muzzle width (RMW), relative length of the upper premolar row (RLUPR) and hypsodonty index (HI). Relative muzzle width was calculated by dividing the mean palatal width by the mean muzzle width (Figure 2). Palatal width (PAW) was measured as the distance between the upper second molars on the lingual side at the level of the protocone. Muzzle width (MZW) was measured as the maximum outer distance of the junction of the premaxillary and maxillary bones. Relative length of the upper premolar row was calculated by dividing the mean premolar row length by the mean molar row length. Premolar row length (PRL) and molar row length (MRL) were measured as the length along the base of the crown on the labial side. Hypsodonty index was calculated by dividing the mean of the unworn height of the second molar by the mean of the width of the second molar. The height was measured on the labial side from the base of the crown to the apex of the protoconid. The width was measured as the distance between the protoconid and the metaconid.

The source for the hypsodonty data for all groups except *Poebrotherium* was Janis (1988). Relative muzzle width and relative length of the upper premolar row data were collected from multiple specimens of the same species. Familiarization of head musculature was made possible by the dissection of a fresh specimen of *Antilocapra americana,* housed in the Georgia College & State University Mammal collection.

Dental wear facets were examined to reveal clues about the types of food comminuted and about jaw movement during mastication (Butler, 1972; Costa and Greaves, 1981; Fortelius, 1985; Greaves, 1973, 1991; Janis, 1990, 1995; Rensberger et al, 1984).

RESULTS

A summary of the data is presented in Table 1. The results obtained from comparing the modern taxa are presented first. The following results were obtained after test-

FIGURE 1. Lateral view of the skull and jaws of *Poebrotherium wilsoni* (GCVP 2119). Scale bar equals two centimeters.

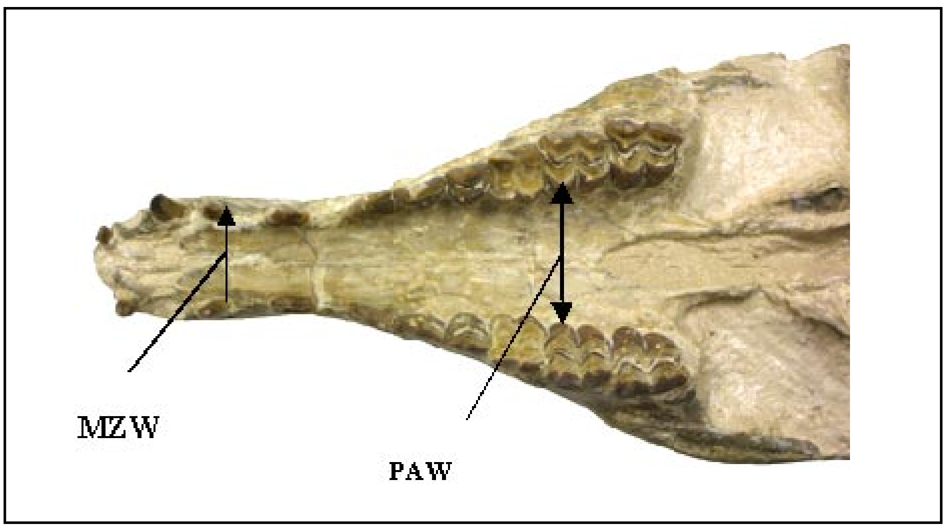


FIGURE 2. Ventral view of skull (GCVP 2679) illustrating cranial measurements taken. Abbreviations: MZW, muzzle width; PAW, palatal width.

ing for significant differences in the mean values of each index (HI, RMW and RLUPR) for each dietary group (browser, mixed feeder and grazer).

The hypsodonty results showed that browsers (1.82) were significantly ($p<0.001$) less hypsodont than grazers (4.34). Mixed feeders (3.02) were intermediate in hypsodonty, but not significantly less hypsodont than grazers (4.34) or significantly more hypsodont than browsers (1.82). Therefore, browsers were distinguished from grazers, but mixed feeders were not distinguished from browsers or grazers.

Study of relative muzzle width produced the following results. Grazers (1.27) had a significantly broader muzzle than either browsers (1.96) or mixed feeders (1.70) $p<0.001$ and $p<0.01$, respectively. Browsers had a narrower muzzle (1.96) than mixed feeders (1.70), but not significantly narrower. Therefore, grazers were distinguished from mixed feeders and browsers, but browsers were not distinguished from mixed feeders.

Analysis of the relative length of the upper premolar row produced the following results. Browsers (0.85) had a significantly ($p<0.01$) longer premolar row than grazers (0.58); mixed feeders (0.71) were intermediate in premolar row length, but not significantly longer than grazers (0.58) nor significantly shorter than browsers (0.85). Therefore, browsers were distinguished from grazers, but mixed feeders were not distinct from browsers or grazers.

The following results were obtained after testing for significant differences between *Poebrotherium* and each dietary group. *Poebrotherium* was the least hypsodont (HI=1.61) of all taxa. It was significantly *($p<0.001$)* less hypsodont than the grazers (mean HI=4.34). It was not significantly less than the mixed feeders (but this may be an artifact of the small sample size since the mixed feeder mean is HI=3.02), nor was it significantly less than the browsers (mean HI=1.82). *Poebrotherium* had a relatively broad muzzle (RMW=1.30), which is significantly ($p<0.05$) broader than the mixed feeders (mean RMW=1.67). However, *Poebrotherium* did not test significantly broader than the narrowest of all groups, the browsers (mean RMW=1.96), but this is probably due to the small sample size. Relative length of the upper premolar row was the greatest in *Poebrotherium* (1.18). It tested significantly greater than the browsers (mean RLUPR=0.85, $p<0.02$), the mixed feeders (mean RLUPR=0.71, $p<0.001$) and the grazers mean (mean RLUPR=0.58, $p>0.01$). In comparative terms, *Poebrotherium can* be described as having a broad muzzle, a long upper premolar row and low crowned molars.

Camelus was analyzed separately from the mixed feeders. *Camelus* was not significantly more or less hypsodont (HI=2.52) than the browsers (mean HI=l.82) or the mixed feeders (mean HI=3.02), respectively. *Camelus* was significantly ($p<0.01$) less hypsodont than the grazers (mean HI=4.34). *Camelus* was not significantly more or less narrow in muzzle width (RMW=1.83) than the mixed feeders (mean RMW=1.67) or the browsers (mean RMW=1.96), respectively. *Camelus* was significantly ($p<0.001$) narrower in muzzle width than the grazers (mean RMW=*1.27*). *Camelus* had a significantly ($p<0.05$) shorter premolar row (RLUPR=0.55) than the browsers (mean RLUPR=0.85). *Camelus* did not have a significantly shorter premolar row than either the mixed feeders (mean RLUPR=0.71) or the grazers (mean RLUPR=0.58). For all indices, *Camelus* was not significantly different from the mixed feeders.

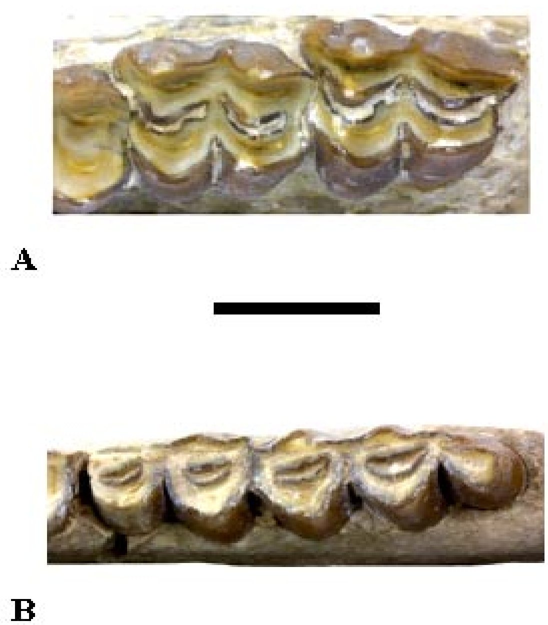


FIGURE 3. A, upper and B, lower dentition of *Poebrotherium wilsoni* (GCVP 2679 and 3819). Scale bar equals one centimeter.

Poebrotherium was significantly different from *Camelus* for all three indices. *Poebrotherium* was less hypsodont (1.61 vs. 2.52 $p<0.02$), in possession of a broader muzzle (1.3 *vs.* 1.83 $p<0.01$) and had a longer premolar row (1.18 vs. 0.55 $p<0.001$).

Dental wear of all the groups was compared, and the following observations summarize the comparisons. The mixed feeders, and to a lesser degree, the browsers, exhibited similar patterns of wear. On the lingual slopes of the endolophs, there were small ovoid facets with fine, parallel striations. *Tragulus sp.* deviated slightly from the other browsers, as it exhibited wear more similar to the mixed feeders. The browsers and the mixed feeders were more similar in having greater occlusal relief, and in abrasion wear.

Examination of the wear facets of *Poebrotherium* (Figure 3) produced the following results. The direction of the jaw movement was inferred by inspecting the enamel-dentine interface. The ectoloph of the upper molar exhibited wear frequently observed in living selenodont artiodactyls. Namely, there was a smooth, uninterrupted enamel-dentine interface at the leading edge and an uneven, abrupt enamel-dentine interface at the trailing edge. The striations etched on the wear facets were directed perpendicular to the enamel-dentine ridges. Wear facets on the slopes of the endoloph were ovoid in shape, and they were positioned more vertically than horizontally. Abrasion wear was characteristic of these teeth.

The wear pattern of *Poebrotherium* molars was similar to the wear of the mixed feeders, specifically, *Hydropotes inermis* and *Muntiacus muntjak.* It should be noted that the browsers and mixed feeders used in this study are all comparable in size to *Poebrotherium*.

DISCUSSION

Poebrotherium wilsoni is a relatively rare member of the ungulate fauna from the Scenic Member of the Brule formation. The relative abundance of this taxon increases significantly to the south and west of Badlands National Park (Honey et al. 1998). The paleoecology of the Scenic Member has been described from fossil soil studies (Retallack, 1983). Paleosol evidence depicts the change from a warm, humid Eocene (55-35 MYIBP) to an increasingly arid Oligocene (35-25 MYBP) marked with episodes of severe drought. Fossil soils also indicate that woodlands were widespread during the early Oligocene with interspersed streams or marsh areas. The vegetation during the deposition of the Scenic Member can be divided into three predominant habitats: swampy streamside swales, with early successional vegetation, an extensive woodland bordering the streams, and a savanna habitat. The savanna habitat was populated with bunch grass and small forbs.

This study was undertaken to determine the likely dietary habits of *Poebrotherium wilsoni* compared to modern selenodont artiodactyls of known dietary habits. For all three indices examined there were significant differences between the browsers and the grazers. The grazers and the mixed feeders were significantly different in only one index, relative muzzle width. The mixed feeders and the browsers did not differ significantly for any index. Qualitatively, the tooth wear differed for each group, but there were greater similarities between the browsers and mixed feeders.

The hypsodonty index for *Poebrotherium wilsoni* (1.61) was least like that of the grazers (4.34). It was not significantly lower than the mixed feeders (3.02), but this is probably an artifact of the sample size. The hypsodonty index for *Poebrotherium* was most similar to the browsers (1.82) as a group. Comparisons with individual taxa are possibly more meaningful. *Poebrotherium* has a hypsodonty index particularly close to *Tragulus sp.* (HI=1.40), a browser, and two mixed feeders *Hydropotes* (HI=1.84) and *Muntiacus* (HI=1.81). *Tragulus*, the mouse deer lives in wooded areas and feeds on the leaves of bushes, fallen fruit and some grass. *Hydropotes*, the Chinese water deer, feeds on a variety of reeds, grasses, and vegetables near streams. *Muntiacus*, the barking deer, lives in dense forests where it feeds on shrubs, grasses, and ripe fruits.

Poebrotherium had the longest premolar row (1.18) of any group measured. *Tragulus sp.* (1.04) was the only modern species that was nearly as long. *Poebrotherium* exhibited abrasion wear indicative of a diet consisting of at least in part, pulpy food items. Dental wear in *Poebrotherium* was most similar to the mixed feeders *Hydropotes* and *Muntiacus* and to a lesser degree to the browser *Tragulus.*

In summary, *Poebrotherium wilsoni* shared more similarities with the browsers and the mixed feeders. From this analysis, it can be reasonably suggested that *Poebrotherium wilsoni* was a browser or a mixed feeder. The difficulty in further clarification rests in the inability to distinguish mixed feeders from browsers with these methods.

Locality data from the literature suggested that *Poebrotherium* frequented a variety of habitats. Clark et al. (1967) collected specimens of *Poebrotherium* from all three principal habitats represented in the deposits (open plain, near-stream woodland, and stream-side swales). Because of its locomotor adaptations, Clark et al. expected *Poebrotherium* to be common in the deposits interpreted as open plains, but they were not expecting to find this taxon in the other habitats. Our extensive fieldwork in the Orellan of the Southern Unit of Badlands National Park confirms the widespread nature of this taxon.

Poebrotherium wilsoni is commonly referred to in paleontological literature for its cursorial adaptations (Webb, 1972). The limbs were elongated, and the front limb was nearly as long as the hind limb. Additionally, the lateral toes were reduced to tiny splints (Scott, 1940; Webb, 1972). These limb modifications are reminiscent of modern cursorial ungulates living in open plains. However, the occurrence of *Poebrotherium wilsoni* in a variety of habitats does not support a strong preference for any one habitat. The cursorial adaptations of this early Oligocene camelid and the later development of digitigrade feet and a pacing gait exhibited in the two Miocene camelids, *Michenia* and *Protolabis,* has been attributed to the success of the group during the transition from a woodland, savanna habitat to an open, grassland habitat. Later forms have been described as becoming more hypsodont with the coinciding spread of grasslands in the Miocene (Webb, 1972).

The modern camels, such as *Camelus dromedarius,* are more hypsodont (2.52) than *Poebrotherium wilsoni* (1.61), and modern camels are mixed feeders. However, the habitat of *Camelus dromedarius,* the Arabian camel or dromedary, is vastly different from the habitats occupied by *Poebrotherium wilsoni,* or the habitats of the other mixed feeders in this study. The dentition of the modern camel is moderately hypsodont, with molarization of premolars three and four, and a leveling of the occlusal surface. The combination of these dental features suggests a coarse diet that is verified through observation (Gauthier-Pilters and Dagg, 1981). In contrast, a low level of hypsodonty, a long premolar row and an occlusal surface of high relief characterize the dentition of Poebrotherium wilsoni. This combination of features suggests a diet consisting of pulpy food items.

CONCLUSIONS

Tooth height, muzzle width and premolar row length all have functional implications related to a particular dietary habit. Interpretation of the craniodental morphology and dental wear of *Poebrotherium wilsoni* has led to the conclusion that *Poebrotherium* was not a grazer. The results indicate a browsing or mixed feeding dietary habit. Modern browsers select a variety of succulent food items; fruit, tender shoots, shrubs, and some grasses. Mixed feeders also take these items, but more of their diet will consist of grasses, shrubs, and in the case of the Chinese water deer, rushes and reeds. Clark et al. (1967) collected *Poebrotherium wilsoni* in deposits that represent three principal habitats: open savanna; near steam woodland; and streamside swales.

TABLE 1.Data summary for cranial and dental indices. The numbers given are the mean, the number of observations, and the standard deviation. Abbreviations: HI, hypsodonty index; RMW, relative muzzle width; RLUPR, relative length of upper premolar row.

Taxon	HI	RMW	RLUPR
Poebrotherium	1.61(5) 0.03	1.30(3) 0.08	1.18(5) 0.17
Browsers	1.82(3) 0.73	1.96(5) 0.54	0.85(4) 0.15
Mixed Feeders	3.02(4) 1.42	1.67(7) 0.23	0.71(7) 0.18
Grazers	4.34(6) 0.78	1.27(8) 0.12	0.58(5) 0.05
Camelus	2.52(4) 0.30	1.83(3) 0.14	0.55(3) 0.05

These habitats and plant communities parallel the habitats frequented by the modern species featured in this study. It is reasonable to suggest that *Poebrotherium wilsoni* may have made seasonal or daily movements selecting a variety of foods from any one of these habitats.

ACKNOWLEDGEMENTS

We thank Ms. Rachel Benton of Badlands National Park for her extensive support of our research efforts and Mr. Vince Santucci for his enthusiasm and support for paleontological research in the National Parks. Three anonymous reviewers provided useful comments on the manuscript. This research was partially funded by faculty research grants from Georgia College & State University.

REFERENCES

Butler, P.M., 1972. Some functional aspects of molar evolution. Evol. 26(3): 474-483.

Clark, J., J.R. Beerbower, and K.K. Kietzke, 1967. Oligocene sedimentation, stratigraphy, paleoecology, and paleoclimatology in the Big Badlands of South Dakota. Fieldiana Geology Memoirs 5:1-158.

Costa, R. and W.S. Greaves, 1981. Experimentally produced toothwear facets and the direction of jaw motion. Journal of Paleontology 55(3):635-638.

Estes, R.D., 1972. The comparative behavior of Grant's Gazelle and Thompson's Gazelle. Journal of Mammalogy 48:182-209.

Fortelius, M., 1985. Ungulate cheek teeth: developmental, functional, and evolutionary interrelations. Acta Zoologica Fennica 180:1-76.

Gauthier-Pilthers, H. and K.L. Dagg, 1981. The Camel: its evolution, ecology, behaviour, and relationship to man. University of Chicago Press: Chicago. 208 pp.

Gazin, C.L., 1955. A review of the upper Eocene artiodactyls of North America. Smithsonian Contributions to Paleontology 5:1-29.

Greaves, W. S., 1973. The inference of jaw motion from tooth wear facets. Journal of Paleontology 47:1000-1001.

_____, 1991. A relationship between premolar loss and jaw elongation in selenodont artiodactyls. Zoological Journal of the Linnean Society. 101:121-129.

Harrison, J.A., 1985. Giant camels from the Cenozoic of North America. Smithsonian Contributions to Paleontology. 5:1-29.

Honey, J.G., J.A. Harrison, D.R. Prothero, and M.S. Stevens, 1998. Camelidae. In: Evolution of Tertiary Mammals of North America Volume 1: Terrestrial Carnivores, Ungulates, and Ungulatelike Mammals (C.M. Janis, K.M. Scott, and L.L. Jacobs, eds.), p. 439-462.

Janis, C.M., 1988. An estimation of tooth volume and hypsodonty indices in ungulate mammals, and the correlation of these factors with dietary preference. In: Teeth Revisited (D.E. Russell, J.P. Santoro, and D. Sigogneau-Russell, eds.). Memoirs de Museum National d'Histoire Naturelle 53: 367-387.

_____, 1990. The correlation between diet and dental wear in herbivorous mammals, and its relationship to the determination of diets of extinct species. In: Paleobiological Evidence for Rates of Coevolution and Behavioral Evolution (A. J. Boucot, ed.). Elsevier: New York. Pp. 241-259

Janis, C.M., 1995. Correlation between craniodental morphology and feeding behavior in ungulates: Reciprocal illumination between living and fossil taxa. In: Functional Morphology in Vertebrate Paleontology (G. J. Thomason, ed.). Cambridge U. Press: Cambridge. Pp. 76-98.

Janis, C.M. and D. Ehrhardt, 1988. Correlation of relative muzzle width and relative incisor width with dietary preference in ungulates. Zoological Journal of the Linnean Society 92:267-284.

Loomis, F.B., 1928. *Poebrotherium.* American Journal of Science 16:137-142.

MacFadden, B.J., 1992. Fossil horses: Systematics, Paleobiology and Evolution of the family Equidae. Cambridge University Press. 369 p.

McKenna, M.C., 1966. Synopsis of Whitneyan and Arikareean camelid phylogeny. American Museum Novitates 2253:1-11.

Nowak, R. M., 1991. Walker's Mammals of the world. Johns Hopkins University Press: Maryland. 1629 pp.

Prothero, D.R., 1994. The Eocene-Ohgocene Transition. Columbia University Press: New York. 283 pp.

_____, 1996. Camelidae. In. The terrestrial Eocene-Oligocene transition in North America (D. R. Prothero and R. J. Emry eds.) Cambridge University Press: New York. Pp. 609-651.

Radinsky, L.B., 1986. Patterns in the evolution of ungulate jaw shape. American Zoologist 25:315-330.

Rensberger, L.B., A. Forsten., and M. Fortelius, 1984. Functional evolution of the cheek tooth pattern and chewing direction in Tertiary horses. Paleobiology 10(4):439-452.

Retallack, G.J., 1983. A paleopedological approach to the interpretation of terrestrial sedimentary rocks: the mid-Tertiary fossil soils of Badlands National Park, South Dakota. Geological Society of America Bulletin 94:823-840.

Schultz, B., 1959. The camel story. University of Nebraska Museum Notes no. 8.

Scott, W. B., 1929. History of Land Mammals in the Western Hemisphere. Macmillan Company, New York. 693 pp.

_____, 1940. Artiodactyla part IV. In: The Mammalian Fauna of the White River Oligocene (W. B. Scott and G. L. Jepsen, Eds.). Transactions of the American Philosophical Society 28:363-746.

Solounias, N. and B. Dawson-Saunders, 1988. Dietary adaptations and paleoecology of the Miocene ruminants from Pikermi and Samos in Greece. Palaeogeography, Palaeoclimatology, Palaeoecology 65:149-172.

Solounias, N., M. Tedford, and A. Walker, 1988. Interpreting the diet of extinct ruminants: the case of a non-browsing giraffid. Paleobiology 14:287-300.

Webb, S.D., 1965. The osteology of *Camelops*. Bulletin of Los Angeles County Museum, no. 1.

_____, 1972. Locomotor evolution in camels. Forma et Functio 5:99-112.

_____, 1974. Pleistocene llamas of Florida, with a brief review of the lamini. In: Pleistocene Mammals of Florida (S. D. Webb, ed.). University Press Florida; Gainesville.

Wheeler, J.C., 1995. Evolution and present situation of the South American Camelidae. Biological Journal of the Linnean Society 54:271-295.

Wilson, J.A., 1974. Early Tertiary vertebrate faunas, Vieja group and Buck Hill group, Trans-Pecos Texas: Protoceratidae, Camelidae, Hypertragulidae. Bulletin Texas Memorial Museum no. 23. 34 pp.

Wortman, J.L., 1898. The extinct Camelidae of North America and some associated forms. Bulletin of the American Museum of Natural History 10:93-142.

APPENDIX 1

Poebrotherium wilsoni: GCVP 258, 263, 264, 2011, 2012, 2118, 2119, 2679, 2704, 3816, 3819, 3879, 3932.

Browsers: GCM *411 Madoqua* sp.; *GCM 17 Odocoileus virginiaus;* GCM *918 Gazella granti*; *Tragulus sp.; Litocranius* sp. (both in a private collection)

Mixed Feeders: GCM *44 Oreotragus oreotragus; GMC* 405, 406 *Hydropotes inermis; GCM* 407, 408 *Muntiacus muntiac; GCM 914 Llama glama; GCM 135 Antilocapra arnericana.*

Grazers: UNSM-16018 *Llama pacos; UNSM-16921 Vicugna vicugna; UNSM-5081 Damaliscus lunatus; UNSM-15514 D. dorcas; UNSM-5019 Kobus kob; UNSM-5023 K ellipsiprymnus; UNSM-15482 Hippotragus niger; UNSM-5070 AIcelaphus buselaphus.* Modern camels: GCM 9741 975, 976 *Camelus dromedarius.*

PALEONTOLOGICAL RESOURCE MANAGEMENT

BASELINE MAPPING OF FOSSIL BONE BEDS AT BADLANDS NATIONAL PARK

RACHEL C. BENTON[1], EMMETT EVANOFF[2], CARRIE L. HERBEL[3], AND DENNIS O. TERRY, JR.[4]

[1]Badlands National Park, Interior, SD 57750
[2]University of Colorado Museum, Boulder, CO 80309
[3]South Dakota School of Mines & Technology, Rapid City, SD 57701
[4]Temple University, Philadelphia, PA 19122

ABSTRACT—Through a three-year grant with the Natural Resources Preservation Program (NRPP), Badlands National Park has begun documenting the extent and location of its fossil resources. Due to the great size of the park and the extent of exposed bedrock, the scope of this project is limited to the lowest horizons within the Scenic Member of the Brule Formation. To date, our team has documented the distribution, composition, stratigraphic position, and depositional setting of numerous fossil sites within three designated areas, covering 3.5 map sections. In the coming years, this survey will provide the basis for an effective paleontological inventory and monitoring program and a predictive model for locating other fossil accumulations within the lower Scenic Member of the Brule Formation. After one summer of fieldwork, 351 new paleontological sites have been documented and recorded into the Park's the Geographic Information System (GIS) database. Many of these sites consist of bone horizons with hundreds of specimens; however, only 231 specimens were collected. The criteria used to collect specmimens included; threats from erosion or poaching and the overall scientific value of the fossil. Six stratigraphic marker beds occur over 30 km^2 of the Scenic Member outcrop. The marker beds provide stratigraphic control for locating fossil localities within 1 meter vertical resolution. A broad spectrum of paleosol development was also noted during the sedimentological survey and it appears that the Scenic Member was deposited on an irregular erosional surface, consisting of several topographic highs and lows. Sedimentological interpretations of particular marker beds and bone horizons will serve as valuable tools for interpreting ancient climates and regional basin evolution.

INTRODUCTION

Paleontological resources were a major reason for originally establishing Badlands National Monument in 1939, for adding the 133,000 acre Stronghold District in 1976, and obtaining National Park status in 1978. Thousands of specimens have been legitimately collected and are housed in museums and universities throughout the world. These fossils have provided valuable information in the understanding of mammalian evolution and diversity, paleoecology and paleoclimates.

For the first time in its history, Badlands National Park has begun the process of documenting the extent and location of its fossil resources. The goals of this project include a paleontological site inventory including the identification and taphonomic analysis of each paleontological specimen found. It also includes the collection of baseline data including stratigraphic position, depositional environment and degree of preservation. This survey is providing the basis for an effective paleontological inventory and monitoring program, as well as a predictive tool for discovering additional fossil accumulations within the lower Scenic Member of the Brule Formation. All locality information has been recorded into the Park's GIS paleontological data layer, which is a database that contains many of the known park paleontological sites. Detailed fossil locality information is omitted in this manuscript to protect paleontological resources at Badlands National Park.

The NRPP bone bed mapping project has provided insight into many aspects of the geology and paleontology of the lower Scenic Member in Badlands National Park. Foremost, we have gained a better understanding of the distribution and condition of fossil resources in one part of the park. From a geologic standpoint, we have gained information on the geologic history, depositional environments, and paleoclimatic conditions at the time these bone beds were formed. The three field teams covered 3.5 map sections within Conata and Tyree Basins and far exceeded their expectations in the number of sites documented, scientifically significant specimens collected and general geologic interpretations made (Fig. 1).

The project has been limited in scope stratigraphically, to gain a better understanding of the depositional setting within the lower Scenic Member of the Brule Formation. Future surveys will be designed to examine other stratigraphic units under a similar approach. The bone beds survey has already generated interest in two additional Masters projects within the lower Scenic Member.

PRIOR RESEARCH IN THE PARK

The long history of research in the White River Badlands has contributed greatly to the science of vertebrate paleontology in North America, beginning with the discovery

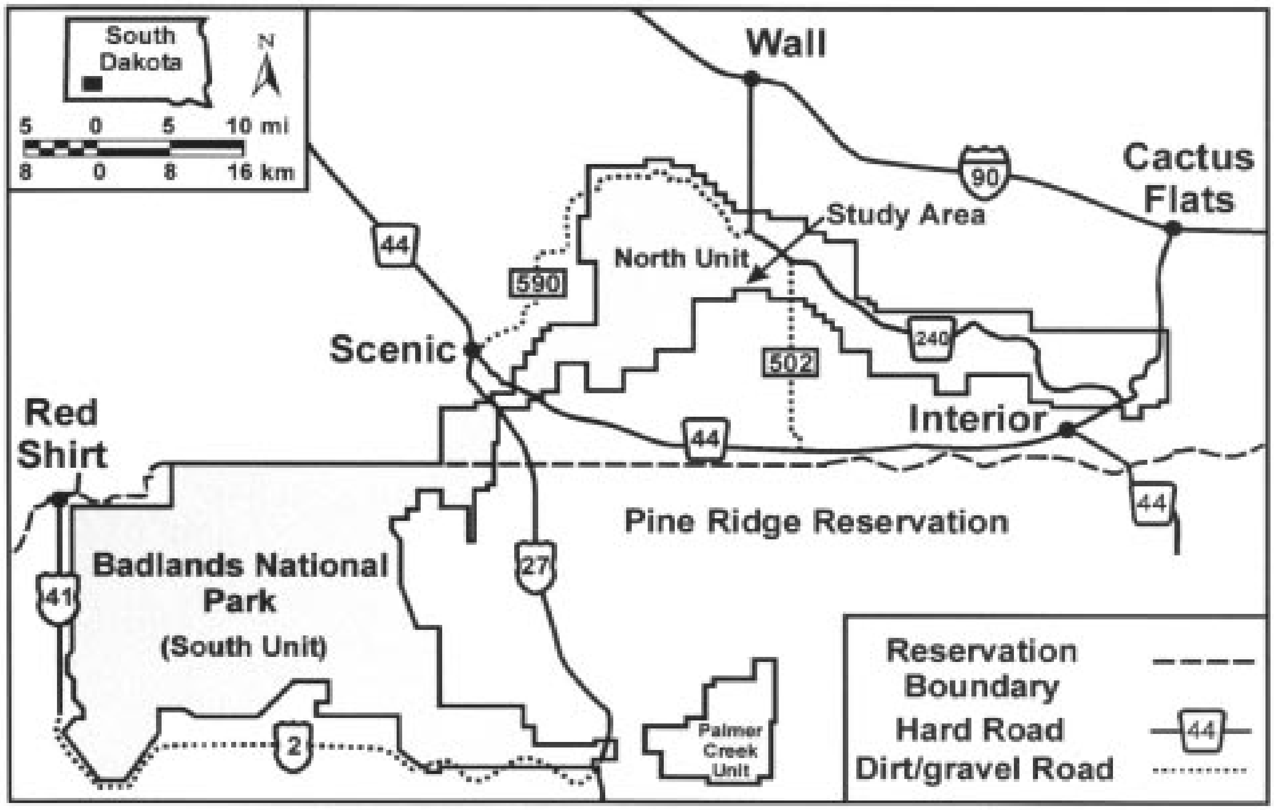


FIGURE 1. Map of Badlands National Park showing the location of the study area (arrow).

and description of a brontothere mandible in 1846 by, St. Louis physician, Dr. Hiram Prout. In 1847, Dr. Joseph Leidy published a description of a small fossil camel collected from the Badlands. Both specimens were collected by Alexander Culbertson of the American Fur Company on his journey between Ft. Pierre and Ft. Laramie. As explorations continued and collections were made of White River fossils, Joseph Leidy would describe the great majority of new taxa that were discovered. Since then, thousands of fossils have been collected and have served to define this geologic interval.

Stratigraphic nomenclature for White River sediments has evolved greatly over the past century of study (Fig. 2). Darton (1899) formally named the Brule Formation after "a series of pink clays" that lie above the Chadron Formation. Bump (1956) divided the Brule Formation into the Scenic Member and the Poleslide Member. The Scenic Member extends between the top of the Chadron Formation and the top of the "upper nodular zone;" and the Poleslide Member which includes the siltstone beds above the Scenic Member and below the Rockyford Ash Member. The "upper nodular zone" was originally described by Osborn and Matthew (1909) and Wanless (1923) as the "upper nodular layer". The development of nomenclature of the White River Group is described in detail by Harksen and Macdonald (1969a, 1969b), Emry and others (1987) and Terry and others (1995).

Several depositional models have been proposed for the origin of the White River deposits. Hayden interpreted the widespread uniform layering of White River Group sediments as the result of lucustrine deposition following the withdrawal of the Cretaceous seas (Tedford, 1970). Based on his studies in Colorado, Matthew (1901) proposed that the White River deposits were mostly fluvial and eolian loess "formed on grass covered prairies." Matthew noted that the White River contained mostly terrestrial faunas and very few aquatic animals within thick siltstone deposits.

Clark and others, (1967) examined the relationship between structural and geomorphic controls on sedimentation in the Badlands. They developed several models for various facies packages found within the area. From the early 1930's through the 1960's, Clark developed extensive paleontological collections from the Badlands to assist with paleoenvironmental interpretations. He felt that many of the earlier paleontological collections lacked the necessary stratigraphic and locality data needed to make valid interpretations.

Recent work on paleosols in the White River Deposits has been performed by Retallack (1983), Terry and Evans (1994) and Terry (1998, 2001). Retallack (1983) developed a soil classification scheme for the White River Group and used these for interpreting climate conditions throughout the Eocene and Oligocene. He established his paleosols on the U.S. Department of Agriculture's standard soil mapping unit, the soil series (Retallack, 1983). He described five different paleosol series for the Scenic Member. Retallack's evidence for soil formation included; fossil root traces, fossil burrows, soil horizons, cracking and veining of soil units, soil structures, concentration of calcareous layers and invertebrate

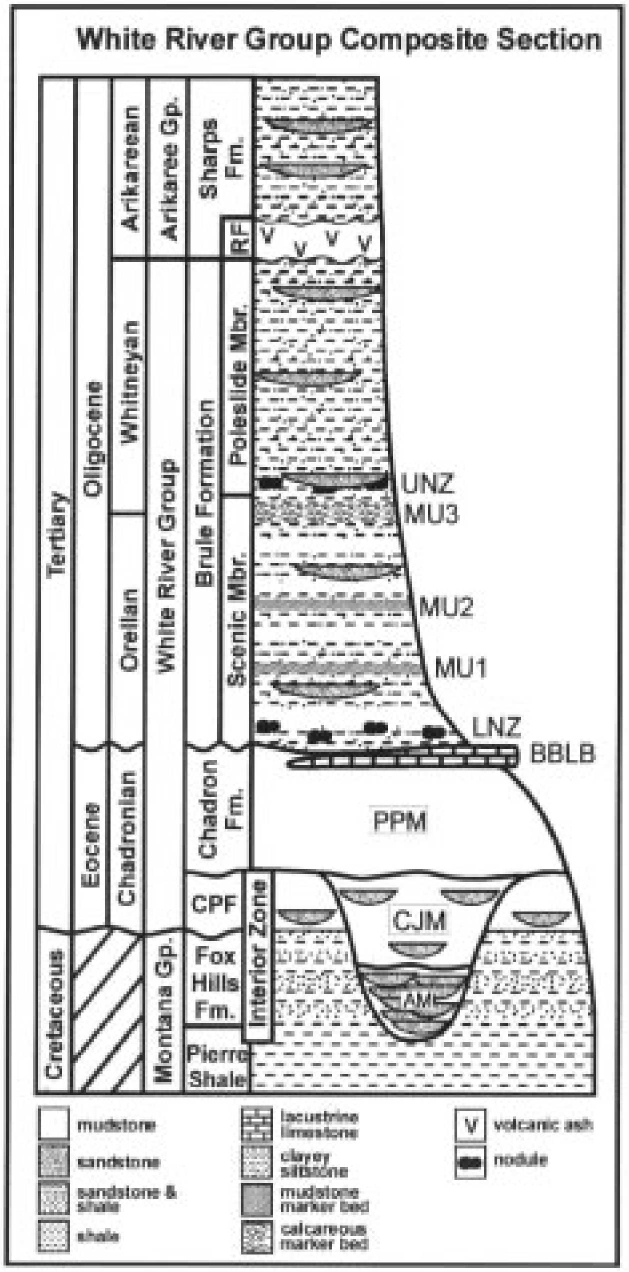


FIGURE 2. Generalized stratigraphic column of the White River Group in Badlands National Park. The column is not to scale, but is drawn instead to show the regional paleogeomorphic relationships of various units. Abbreviations as follows: AM, CJM, and PPM = the Ahearn, Crazy Johnson, and Peanut Peak Members of the Chadron Formation, respectively. BBLB = Bloom Basin Limestone Beds, CPF = Chamberlain Pass Formation, LNZ = Lower Nodular Zone, MU = marker unit, RF = Rockyford Ash, UNZ = Upper Nodular Zone.

remains and burrows. The work of Terry and Evans (1994), described lateral changes in paleosol types within the Chamberlain Pass Formation of Evans and Terry (1994). They concluded that paleosols of the Chamberlain Pass Formation could be divided into proximal and distal floodplain settings, each with distinctive pedological characteristics. Terry (in press) evaluated a series of paleosols across the Eocene/Oligocene boundary in the White River Deposits of NW Nebraska. He found that paleosols record a shift from humid to dryer conditions across the Eocene/Oligocene boundary, and that certain parts of the strata found in Nebraska are not preserved in the Big Badlands of South Dakota.

Kruse (1996, 1997) tested the model proposed by Retallack (1983), that fossils from the Scenic Member accumulate and are preserved on old land surfaces. Kruse proposed an alternative model that the mechanisms responsible for the accumulation of fossils in the Scenic Member in Conata Basin are the product of flood transport and later soil development.

The contact between the Chadron and Brule Formations is marked by a regional unconformity that lasts at least 400,000 years, but maybe as long as 1 My, in duration (Prothero and Whittlesey, 1998). This unconformity produced paleotopography on the underlying Chadron Formation. Once deposition resumed, the Scenic Member of the Brule Formation filled in the uneven ancient land surface. Some parts of the Scenic Member are thicker than others due to the infilling process. We are presently using magnetostratigraphy, to determine the temporal relationships of the subunits of individual bone beds in the Scenic Member above this unconformity.

Many of the fossils from the White River Badlands appear to be concentrated as bone beds within a fairly thin stratigraphic layer within the Scenic Member of the Brule Formation. One of these bone beds, known as the Conata Picnic Area Paleontological Site, or the “Big Pig Dig”, was discovered in 1993. The site is a dense accumulation of fossils which differ from the traditional models for bone preservation (i.e. attritional bone accumulations on ancient ground surfaces or fluvial accumulations within ancient channel systems). The bones instead occur as semi-articulated to disarticulated elements which show no preferred orientation (Stevens, 1995; Stevens 1996a, 1996b). The site has moderate diversity with the bones of several types of animals greatly intermixed. Based on the sedimentary analysis completed by Terry (1996a, 1996b) the site is interpreted as a watering hole. These conclusions are based on the relict bedding lamination, the lenticular shape of individual units and the lack of pedogenic features such as root traces, soil structure, soil fabric and geochemical trends within the bone bed. Thousands of fossils have been collected from this site and valuable information on bone preservation and accumulation has also been acquired (Bjork, 1994-1996; Herbel, 1997-1998). The information from the Big Pig Dig is currently being compared with sites of similar origin in Northeastern Colorado. Further surveys have indicated that several other bone beds of similar significance occur in the park but are less completely documented.

Several sites within the Badlands Wilderness Area were originally documented by Clark and others (1967) and later by surveys the South Dakota School of Mines and the Denver Museum of Nature and Science. One of the newest locations is the Brian Maebius bone bed within Tyree Basin. In contrast to the Pig Dig, this site contains a greater diversity of fauna along with trace fossils (coprolites), pollen and fossilized wood (DiBenedetto, 1997, 1998, 2000, DiBenedetto and Wrenn, 2000). Fossils were deposited in discrete pods or surface swales and many individual bones contain gnaw marks from scavenging activity. Paleosols are easily identified at the site as indicated by coprolites, root casts and *in situ* fossil tree stumps. A detailed analysis of the paleosols is currently underway.

PALEONTOLOGICAL SITE SURVEY

Objectives - The objectives of the paleontological site survey are to document the fossil resources within the confines of the lower Scenic Member of the Brule Formation in select sections of the North Unit of Badlands National Park. The paleontological field team also developed methodologies to be used for future paleontological field documentation. The localities selected for this study are highly fossiliferous and easily accessible from nearby roads and visitor areas. By doing a thorough baseline mapping and fossil survey, the staff at Badlands National Park can identify areas that are threatened now, in the near future, or are potentially stable for many years to come.

This survey will attempt to develop a basic understanding of how these sites fit into the overall geologic time scale and regional depositional models. These sites will also be used as a predictive model when looking for new paleontological sites within the selected study area.

Methods - The paleontological team divided into two or three groups of 2 to 3 individuals each (Fig. 3). One team of two members was in charge of collecting GPS field data. Other teams prospected new areas for vertebrate fossils and documented fossil sites on aerial photographs and within field notebooks. Other information, such as associated geological, stratigraphic and bone surface features, were also noted. Bone horizons, bone beds, and important single fossil specimens were flagged to alert the GPS team. The GPS team would follow the prospecting team(s) and entered locality data in the form of a point, line or polygon within the GPS units. The GPS data will be integrated into a GIS layer and incorporated into the final report to the Park at the end of the three-year project.

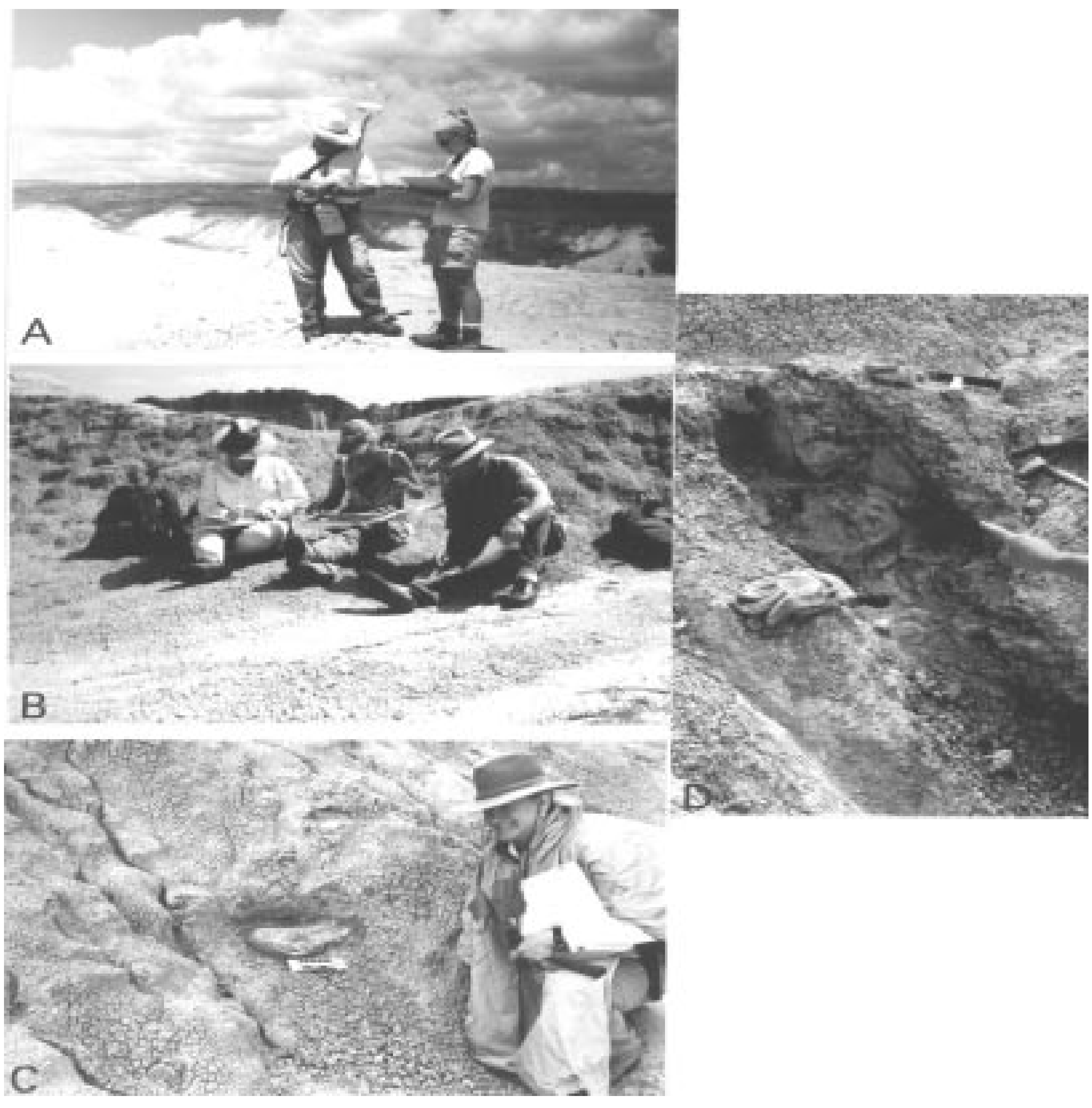


FIGURE 3A. Joe DiBenedetto and Sarah Black collecting GPS data. 3B. Carrie Herbel, Ellen Stark, and Jerry Mundt reviewing aerial photos. 3C. Partially poached fossil tortoise. 3D. Trench exposing unweathered portions of the lower Scenic Member at the Brian Maebius Site.

After noting position, the fossils were also identified to family or genus as well as element, and examined for taphonomic information (weathering, bone modification, fracture pattern, position within the bone bed, etc.). Additional documentation such as photographs and measurement within the section was also gathered. Specimens of scientific importance were collected. However, collecting was kept to a minimum because of the scope of the project. Each bone locality was plotted on detailed aerial photographs at a scale of 1:2400.

Specimens collected - Although the primary goal of the project was not to collect specimens unless scientifically significant, many fossils proved to be so. The 231 specimens that were collected, were threatened by erosion or poaching (well-traveled areas), and were scientifically important (e.g. *Agriochoerus* jaw). Bone modification by carnivores was noted on several specimens. A small number of skulls were jacketed with plaster bandages. All specimens are currently at the South Dakota School of Mines Museum of Geology's Vertebrate Preparation Laboratory and are being cleaned and stabilized for later analysis.

Number of new sites - Several new fossil sites were discovered within the lower part of the Scenic Member of the Brule Formation. A total of 351 new sites were documented during the first field season. Each plotted fossil site does not signify only one fossil. In many cases, a bone horizon was plotted as a line along the outcrops using the GPS unit. In several others, polygons plotted by the GPS unit encompassed a larger area of fossil accumulations. Several major multi-taxa bone beds were assigned locality names. Of additional interest, turtle fossils occurred in nearly every section surveyed and ranged from complete to partial shells, some of which were highly fractured. Extensive turtle/tortoise horizons could be traced over great distances. Some of these were plotted as a single line in many areas, while others as a single point. Only a few turtle specimens were collected during the first field season. Those not collected were either extremely large and/or highly fractured and were in poor condition.

DISCUSSION

Only the lowermost portion of the Scenic Member was surveyed in this project. Cursory examination of the upper sections proved that they contain some fossil material; however, the steepness of the upper Scenic outcrops and the need to focus on a discrete section eliminated these areas from the thrust of this study. In addition, the much greater threat of poaching in the lower section of the Scenic increases the necessity of documentation when surveying these sections. The major fossil-bearing units fall below a marker bed (marker unit 1) (Fig. 2) that occurs throughout and between the areas studied by the paleontological survey team. This marker unit is directly above the majority of the fossil-bearing strata and stratigraphically defines the lower Scenic member.

One of the major goals of this project is to provide information to the management team at Badlands National Park on the location of easily accessible fossil resources so that fossil sites within the Park can be protected. The data collected will assist park staff in monitoring sensitive fossil-rich areas and bone bed localities. In addition, the park paleontological staff can address various issues regarding these sites with knowledge garnered from this mapping project. After completing the first year of this 3-year project, results are already visible. GPS data and field notes have already been converted into a GIS layer usable by park staff. New insights into bone bed concentrations are currently being explored in great detail through projects developed by graduate students. These studies may be used as predictors of bone bed occurrences within the lower Scenic Member throughout the park.

STRATIGRAPHIC ANALYSIS

Objectives - The purpose of the Stratigraphic Studies portion of the Baseline Mapping of Fossil Bone Beds Project is to recognize the detailed four-dimensional relations of rock units within the Scenic Member of the Brule Formation in the North Unit of Badlands National Park.. Documenting the stratigraphy is essential to understanding the position in space and time of the fossil-rich horizons within the most fossiliferous part of the White River Group. Stratigraphic analysis of the lower part of the Scenic Member compliments the associated paleontological survey and the sedimentology studies. As a result of the current stratigraphic work, the nomenclature of the Brule Formation will require revision. Previous studies based on work in limited areas can be understood in a broader regional framework, and patterns of bone accumulation are better known and may allow for prediction of occurrence in unstudied areas.

Methods - The area of study included the Hay Butte, Deer Haven, Dillon Pass, and northern Conata Basin areas, extending from sec. 2, T. 3 S., R. 16 E. on the southeast end to sec. 28, T. 2 S., R. 15 E on the northwest end. This study area includes the areas studied by the paleontological survey and the exposures between them. By the end of the field season, 6 stratigraphic marker horizons were documented in the Scenic Member, 30 square km of outcrops were mapped, and 20 stratigraphic sections were measured.

Results - Six widespread stratigraphic contacts and marker units occur in the Scenic Member of the Brule Formation in the Hay Butte to Dillon Pass area of the Park. They include the Chadron/Brule contact, three widespread mudstone horizons, the contact between typical Scenic Member mudstone beds and siltstone beds more typical of the Poleslide Member, and the "upper nodular zone," a widespread sequence of sandstone beds with a top contact that forms the traditional top of the Scenic Member. The stratigraphic position of the scattered fossil accumulations can be determined by their positions relative to these marker units, typically to a resolution of less than 1 m.

SUBDIVISIONS OF THE SCENIC MEMBER

The marker units in the Scenic Member provide stratigraphic boundaries for the lower, middle and upper parts of the Scenic Member. The top contact of the Scenic Member is as yet uncertain, but the siltstones and the "upper nodular zone" traditionally included within the Scenic Member should be assigned to the Poleslide Member by lithologic criteria.

The lower Scenic Member is defined as the rocks between the contact with the underlying Chadron Member and the top of the first marker bed , called marker unit 1. Marker unit 1 is a widespread greenish gray noncalcareous mudstone bed containing abundant mudstone and claystone rip-up clasts and root traces, and scattered white limestone stringers. The lower Scenic ranges in thickness between 25 m in the deepest part of paleovalleys cut into the Chadron Formation, to a minimum of 8.7 m along the highest crests of the erosional paleotopography developed on the Chadron Formation. Lower Scenic rocks in these uplands include basal, red to brown clayey mudstone beds weathered to a strong popcorn surface (reflecting a high amount of swelling clays) that grades into tan massive mudstone beds which locally contain abundant bones. Basal clayey mudstones also floor the sequences in lower Scenic paleovalleys, but they are capped by a well-bedded sequence of red mudstone beds, red to gray, typically platy claystone beds, and interbedded thick very light gray sandstone and light brown-gray muddy sandstone beds. A well exposed cross section (Fig. 4) through a lower Scenic paleovalley sequence is seen in the northern Conata Basin between the Pig Dig (NW¼ sec. 34, T. 2 S., R. 16 E.) and the site of Retallack's (1983) measured section (SE¼ sec. 20, T. 2 S., R. 16 E.).

The middle Scenic is bounded by the top of marker unit 1 and the base of marker unit 3. Marker unit 3 is a very thick sequence of buff brown to green noncalcareous clayey mudstones interbedded with thin white limestone stringers and limestone beds. The base of the first limestone bed marks the top of the middle Scenic. The middle Scenic can be further subdivided into two parts by a mudstone marker bed (marker unit 2). The primary lithologies of the middle Scenic are very light gray very fine to fine sandstone beds interbedded with light brownish gray muddy sandstone beds. Secondary lithologies include gray to red, blocky to platy claystone beds and brown mudstone beds near the top. Marker unit 2 is a thick, brown, noncalcareous mudstone bed with green mottles and numerous claystone rip-up clasts. Thicknesses of the subdivisions of the middle Scenic vary widely. The lower middle Scenic ranges from 10.1 to 18.2 m thick, with a regional trend of thickening to the west (Fig. 5). The upper middle

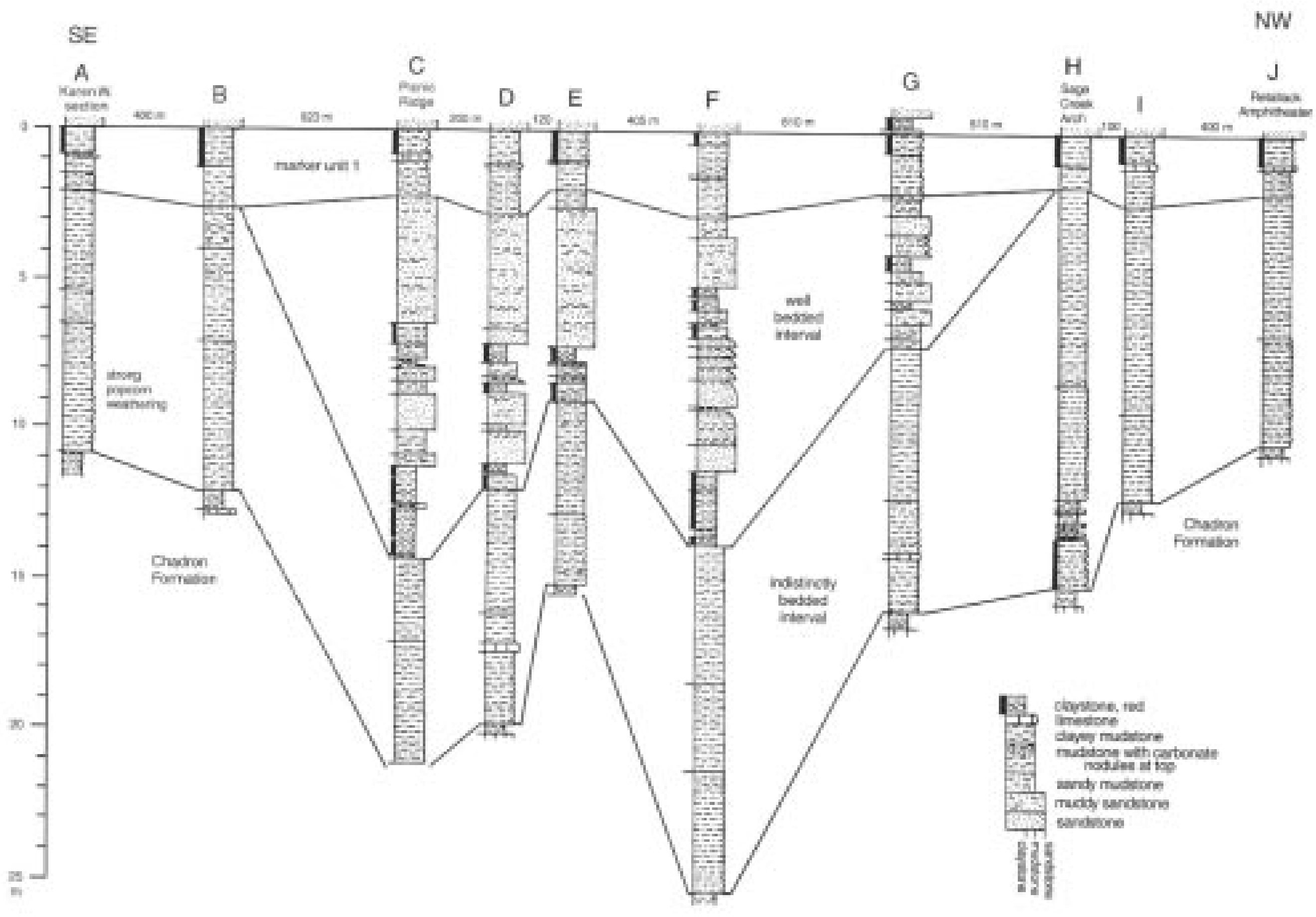


Figure 4. A series of stratigraphic sections through the lower Scenic Member extending from near the Pig Dig (Karen W. section) to the stratigraphic section described by Retallack (Retallack Amphitheater). What is shown is the thickness variations and depositional features of the lower Scenic as it filled a paleovalley cut into the Chadron Formation. The total length of the cross section is 3.4 km. See Figure 5 for the location of this cross section.

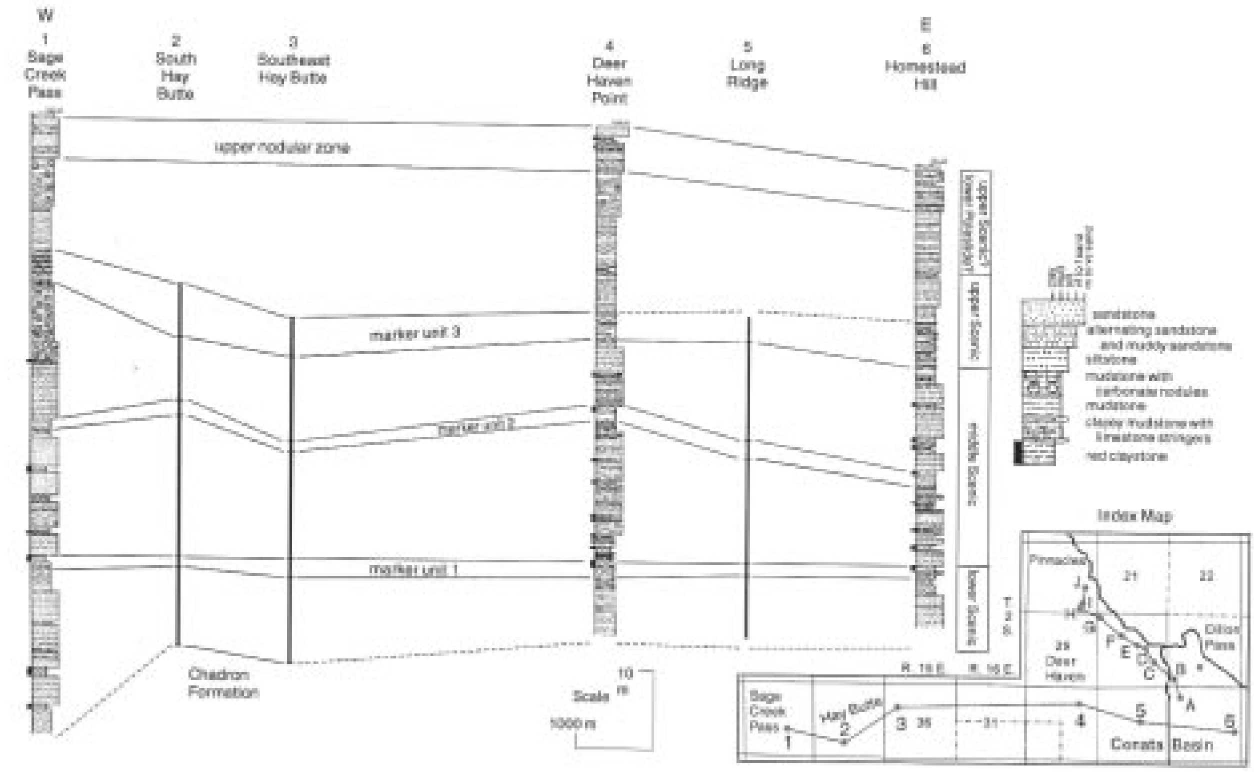


FIGURE 5. West to east cross section showing the distribution of marker beds in the Scenic Member from Sage Creek Pass to Conata Basin. The lithologies of the three most complete sections are shown. In many places the upper Scenic outcrops are unaccessible because of their steepness. The index map shows the locations of these sections (numbered sites) and the locations of the sections of Figure 4 (lettered sites).

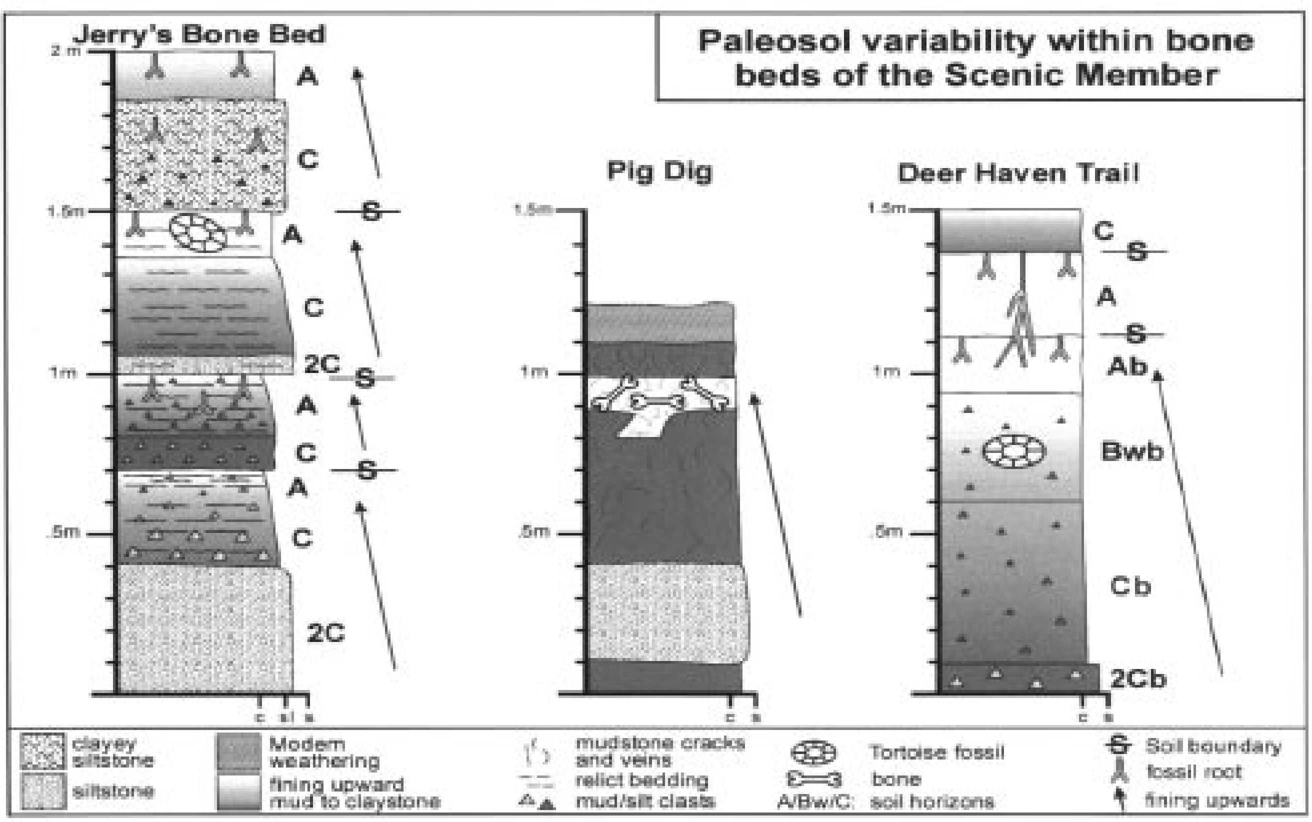


FIGURE 6. Paleosol profiles associated with bone beds of the Scenic Member. Note that fossils occur at different positions within the profiles. A/C profiles are weakly developed soils, whereas A/Bw/C profiles are slightly more developed. Also note that the Pig Dig shows no signs of ancient soil formation.

sequence ranges from 8.1 to 17.4 m with no regional trends. The thick sandstone beds represent broad channel belt complexes. The claystone and mudstone beds represent overbank deposits.

The upper Scenic Member is the sequence from the base of marker unit 3 to the base of the Poleslide Member (Fig. **5**). The traditional top contact of the Scenic is the top of the light gray sandstone beds of the "upper nodular zone" (Bump, 1956). However, thick, massive siltstone beds typical of the Poleslide Member occur on average 5.3 m below the base of the "upper nodular zone" in the study area. These siltstones overlie a sequence of buff to tan typically clayey mudstone beds that lie above the uppermost limestone of marker unit 3. A lithologically more consistent boundary between the Scenic and Poleslide members would be the distinct contact between these mudstone and siltstone beds that occurs on average 11.9 m above the base of marker unit 3. This project will resolve this nomenclature problem after more regional stratigraphic studies are completed.

DISTRIBUTION OF FOSSILIFEROUS UNITS

The rich fossil assemblages of the Scenic Member are strongly associated with certain lithologies and stratigraphic units. Most of the rich bone accumulations occur in mudstone beds, either near the base of the Scenic member or directly below the widespread marker units. The most fossiliferous units include the basal brown to red mudstones informally called the "lower red layer" associated with the basal Scenic at the base of the paleovalley fills. The Pig Dig is associated with these "lower red" mudstone beds. Bone is also common in the massive tan mudstone beds of the lower Scenic on top of the Chadron Formation paleotopographic highs. Mudstone beds directly below marker unit 1, especially in the western Hay Butte area, are locally very fossiliferous and include the Brian Maebius site. Mudstones directly below marker units 2 and 3 on the west side of Hay Butte also have locally rich bone accumulations. Bones are almost always abundant in the siltstones just below the "upper nodular zone." The sandstones and claystones in the lower and middle Scenic are not bone rich. Bones can occur in the widespread marker units, but they are typically rare. Thus, the fossil assemblages occur in discrete stratigraphic intervals separated by poorly fossiliferous rocks.

NEW INSIGHTS ON PREVIOUS STUDIES

The regional stratigraphic perspective from this study brings new insight on previous studies of the Scenic Member. A good example is a reevaluation of the significance of the paleosols described by Retallack (1983). Marker unit 1, one of the most widespread units in the region, was considered a paleosol with a limited distribution indicating original wet local environments by Retallack (soil 23, a Gleska clay silty variety). Retallack reports (p. 31-32) that this soil "has been traced as far south as Conata Picnic Ground where it appears to be changing laterally into a Conata Series paleosol in a fossilized catena." He also reports that the Gleska Series soils in the Scenic member are lateral to channel deposits and grade into the weaker Conata Series paleosols which represent flood basin soils. Neither of these are corroborated by this study, for marker unit 1 retains its high clay content and soil features throughout the study area (even by the Conata Picnic Ground), and it is not associated with any channel deposits in the study area. Instead of representing a local environment, marker unit 1 probably reflects a regional change to wetter environments during depositional stability, allowing widespread forests to cover the area. Such changes may reflect long-term paleoclimatic variations (see the discussion below).

SEDIMENTOLOGICAL ANALYSIS

Soils in modern settings form from the interactions of five main factors: climate, organisms, relief, parent material, and time. This results in a soil profile that has distinct physical, chemical, and biological characteristics manifested as a vertical sequence of horizons within the profile. Common horizons include the A Horizon, a zone of mineral matter and organics at the top of a soil profile, the B Horizon, a zone of accumulation within the middle of the profile that forms by the downward movement of materials through the profile, and the C Horizon, which represents the least amount of alteration. Modern soils are classified into twelve main categories (soil orders) representing soil formation in humid to arid, and hot to cold environments. These in turn can be subdivided into increasingly more distinct soils representing particular changes in the five factors of soil formation (e.g. drainage, topography, and parent materials). In certain situations, soils can be buried and *fossilized* in the geologic record. These ancient soils, or paleosols, have preserved within them the clues to their original environment.

Paleosols are very common in ancient fluvial deposits, such as those in Badlands National Park. Since paleosols are the result of ancient soil forming conditions, they can be used to interpret the genesis of fossil bone beds by looking at the position of bones within an individual paleosol profile, as well as assessing their preservational state (degree of weathering, articulation, diversity). Common end-member associations of bones and paleosols in the White River Group include isolated bones at the top of profiles due to attritional accumulation on an ancient landscape, articulated skeletons within the middle of a profile due to catastrophic burial and subsequent pedogenic overprinting, and channel/proximal floodplain deposition of bones as clasts that have been reworked by lateral migration.

Objectives - The sedimentological field team documented the lithologic component of each of the major or informally named paleontological sites found within the Tyree and Conata Basin study areas. Each site was incorporated into the regional geology extending from Conata Basin, across the wilderness area and into Chamberlain Pass. Detailed studies of lithologies associated with the most significant bone accumulations were made by the sedimentological field team to determine depositional and preservational settings. Such features as layer thickness, lateral extent, rock type, bedding features and ancient soil features will be documented from exposed surfaces and through the use of test pits.

Methods - Nine trenches were excavated, described, and sampled for sedimentology and paleopedology. Five trenches were at the Brian Maebius Site, one was approximately 300 meters to the north of the Mabius Site within the "lower red layer" named the Buffalo Alley Bone Bed, and the remainder were within the "lower red layer" in Conata Basin. These include a site approximately 300 meters to the north/northeast of the Pig Dig in Dillon Pass, a site just south of the access trail to Deer Haven, and a site located in southeastern Conata Basin named Jerry's Bone Bed. Approximately 100 samples were collected from 16 paleosol profiles. In almost every case, bone material could be related to a definite position within a paleosol profile. As of yet we have not determined any preference for position vs. profile type, or degree of bone preservation/modification.

PRELIMINARY FINDINGS

Paleosols in the lower Scenic Member ranged from extremely weak to extremely strong development (Fig. 6). The weakest degree of development (AC profiles to azonal: Entisols within the U.S.D.A Soil Taxonomy, 1998) was seen in southeastern Conata Basin (Jerry's Bone Bed). The strongest development (ABC profiles: Inceptisols within U.S.D.A Soil Taxonomy, 1998) was seen in the Brian Mabius Site. Of particular interest is the marker unit 1. Although not intimately associated with bone accumulation, the areal distribution and extreme pedogenic development (ABtC: Alfisols within the U.S.D.A Soil Taxonomy, 1998) of marker unit 1 throughout Tyree and Conata Basins may serve as a tool for interpreting the dynamics of regional basin evolution. This in turn may be a controlling factor on the genesis of these bone beds. Marker unit 1 is also interesting for the environmental conditions suggested by its paleopedology. Marker unit 1 contains an extremely well developed argillic horizon (Bt), a subsurface accumulation of clay material created by downward percolation of soil water. This type of soil forms under humid, forested conditions. Our present paradigm states that the Eocene/Oligocene transition was marked by a change to cooler and drier conditions (Prothero, 1994). Further study of marker unit 1 my help us refine the dynamics of this climatic change.

ACKNOWLEDGEMENTS

This project would not have been possible without the funding from the Natural Resources Preservation Program managed by the National Park Service. We would also like to thank the Superintendent of Badlands National Park, William R. Supernaugh for granting the three field teams access to National Park Service Lands. Field and lab work would not have been possible without the dedicated efforts of the following graduate students: Andrew Anderson, Jennifer Haessig, and Dave Daitch (Stratigraphic field team); Sarah Black, Ellen Starck, Jerry Mundt, Rob Meredith and Joe DiBenedetto (Paleontological Field Team); Lewis Factor (Sedimentological Field Team). Sarah Black and Lewis Factor have developed Masters research directly related to the project.

REFERENCES

Bjork, P.R., 1994, 1995, 1996. Annual Reports for Summer Field Excavation of the Pig Dig at Badlands National Park, On file in the Badlands National Park Library.

Bump, J.D., 1956. Geographic Names for Members of the Brule Formation of the Big Badlands of South Dakota. American Journal of Science, 254:429-432.

Clark, J., J.R. Beerbower and K.K. Kietzke, 1967. Oligocene Sedimentation, Stratigraphy, Paleoecology and Paleoclimatology in the Big Badlands of South Dakota. Fieldiana: Geology Memoirs, Vol. 5, Field Museum of Natural History, 158 p.

Darton, N.H. Preliminary Report of the Geology and Water Resources of Nebraska West of the One Hundred and Third Meridian. United States Geological Survey Nineteenth Annual Report (1897-1898), 4:719-814.

DiBenedetto, J.N., 1997. Preliminary Investigation of the Stratigraphy, Fauna and Taphonomy of the Brian Maebius Site, Tyree Basin, Badlands National Park, South Dakota. Final Report for Geologist in the Parks Internship, On file in the Badlands National Park Library, 32 p.

_____, 1998. An Oligocene Tree Stump From Badlands National Park, Scenic Member of the Brule Formation, Interior, South Dakota. Abstracts with Programs, The Fifth Conference on Fossil Resources: Partners Preserving our Past, Planning Our Future, p. 14.

_____, 2000. The Sedimentology and Taphonomy of the Brian Maebius Site, Badlands National Park, Pennington County, South Dakota. Unpublished Masters Thesis, South Dakota School of Mines and Technology, 137 p.

DiBenedetto, J.N. and J.H. Wrenn, 2000. The Sedimentology and Taphonomy of the Brian Maebius (BM) Site, Tyree Basin, Sage Creek Wilderness Area, Badlands National Park, Interior, South Dakota. Abstracts with Programs, GSA National Meetings, Reno Nevada, Abstract No. 52631.

Evans, J.E. and D.O.Terry, 1994. The Significance of Incision and Fluvial Sedimentation in the Basal White River Group (Eocene-Oligocene), Badlands of South Dakota. Sedimentary Geology 90:137-152.

Emry, R.J., L.S. Russell, and P.R Bjork, 1987. The Chadronian, Orellan and Whitneyan North American Land Mammal Ages, p. 118-152.. *In* Woodburne, M.O. (ed.), Cenozoic Mammals of North America, University of California Press, Berkeley.

Harksen, J.C. and J.R. Macdonald, 1969a. Guidebook to the Major Cenozoic Deposits of Southwestern South Dakota, Guidebook 2, South Dakota Geological Survey, Vermillion, South Dakota, 103 p.

_____ and _____, 1969b. Type Sections of the Chadron and Brule Formations of the White River Oligocene in the Big Badlands of South Dakota. South Dakota Geological Survey, Report of Investigations, Vol. 99, 23 p.

HERBEL, C.L., 1997 and 1998. Annual Reports for the field excavation, lab preparation and curation of fossils collected from the Pig Dig. On file within the Badlands National Park Library.

KRUSE, G.W., 1996. Surface Textures of Fossil Bone in Fluvial and Floodplain Facies in the Lower Scenic Member of the Brule Formation, White River Badlands, South Dakota. In: Abstracts with Programs Geological Society of America Rocky Mountain Section, 28:4:14.

KRUSE, G.W., 1997. Deposition of the Lower Scenic Member, Brule Formation, in Conata Basin, Badlands National Park, South Dakota. Unpublished Masters Thesis, South Dakota School of Mines and Technology, Rapid City, South Dakota, 84 p.

LEIDY, J., 1847. On a New Genus and Species of Fossil Ruminantia: *Poebrotherium wilsoni*. Academy of Natural Sciences, Phil. Proc., 3:322-326.

MATTHEW, W.D., 1901. Fossil Mammals of the Tertiary of Northwestern Colorado. American Museum of Natural History, Memoir 1:353-447.

OSBORN, H.F. AND W.D MATTHEW, 1909. Cenozoic Mammal Horizons of Western North America by Henry Fairfiled Osborn with Faunal Lists of the Tertiary Mammalia of the West by William Diller Matthew. U.S. Geol. Survey, Bull. 361, 138 p.

PROTHERO, D.R., 1994. The Eocene-Oligocene Transition: Paradise Lost, Critical Moments in Paleobiology and Earth History Series, Columbia University Press, New York, 291 p.

PROTHERO, D.R. AND K.E. WHITTLESEY, 1998. Magnetic Stratigraphy and Biostratigraphy of the Orellan and Whitneyan Land Mammal "Ages" in the White River Group, p. 39-63. *In*: D.O. Terry, H.E. LaGarry and R.M. Hunt (eds.), Depositional Environments, Lithostratigraphy and Biostratigraphy of the White River and Arikaree Groups Geological Society of America Special Paper, Vol. 325.

PROUT, H.A., 1846. Gigantic *Palaeotherium*, American Journal of Sciences, series 2(2): 288-289.

RETALLACK, G.J., 1983. Late Eocene and Oligocene paleosols from Badlands National Park, South Dakota, Geological Society of America, Special Paper 193:1-82.

SINCLAIR, W.J., 192., The "Turtle-Oreodon Layer" or "Red Layer" a contribution to the Stratigraphy of the White River Oligocene: American Philosophical Society Proceedings, 63:94-133.

STEVENS, K.K., 1995. An Orellan Fossil Site in the Scenic Member of the Brule Formation, White River Group, South Dakota. Abstracts with Programs, Geological Society of America Meetings North-Central and South-Central Sections, p. 88.

_____, 1996a. Taphonomy of an Orellan (Early Oligocene) Fossil Assemblage in the Scenic Member, Brule Formation, White River Group, Badlands National Park, South Dakota. Abstracts with Programs Geological Society of America Rocky Mountain Section, 28:4:39.

_____, 1996b. Taphonomy of an Early Oligocene (Orellan) Vertebrate Assemblage in the Scenic Member, Brule Formation, White River Group, Badlands National Park, South Dakota. Unpublished Masters Thesis, South Dakota School of Mines and Technology, Rapid City, 103 p.

TEDFORD, R.H., 1970. Principles and Practices of Mammalian Geochronology in North America: Proceedings of the North American Paleontological Convention, Part F:666-703.

TERRY, D.O., JR., 1996a. Stratigraphic and Paleopedologic Analysis of Depositional Sequences within the Pig Wallow Site, Badlands National Park, Final Report for NRPP Grant on file in the Badlands National Park Library, 164 p.

_____, 1996b. Stratigraphy, Paleopedology and Depostional Environment of the Conata Picnic Ground Bone Bed (Orellan), Brule Formation, Badlands National Park, South Dakota. In: Abstracts with Programs, Geological Society of America Meetings, Rocky Mountain Section, 28:4:40.

_____, 1998. The White River Group of Northwestern Nebraska: Stratigraphic Revisions, Correlations and Paleopedology. PHD. Dissertation, University of Nebraska Lincoln, 248 p.

_____, 2001. Paleopedology of the Chadron Formation of Northwestern Nebraska: Implications for Paleoclimatic Change in the North American Midcontinent across the Eocene-Oligocene Boundary: Paleogeography, Paleoclimatology, Palaeoecology, p. 1-38.

TERRY, D.O., JR. AND J.E. EVANS, 1994. Pedogenesis and paleoclimatic implications of the Chamberlain Pass Formation, Basal White River Group, Badlands of South Dakota, Palaeogeography, Paleoclimatology, Paleoecology , 110:197-215.

TERRY, D.O., JR., H.E. LAGARRY. AND W.B.WELLS, 1995. The White River Group Revisited: VertebrateTrackways, Ecosystems, and Lithostratigraphic Revision, Redefinition and Redescription, p. 43-57. *In* Flowerday, C.A. (ed.), Geologic Field Trips in Nebraska and Adjacent parts of Kansas and South Dakota, Parts of the 29th Annual Meetings, North-central and South-central Sections, Geological Society of America: Conservation and Survey Division Guidebook No. 10, Institute of Agriculture and Natural Resources, University of Nebraska, Lincoln, NE.

WANLESS, H.R., 1923. The Stratigraphy of the White River Beds of South Dakota. American Philosophical Society Proceedings, Vol. 62, 269 p.

THE CASE OF "BIG AL" THE *ALLOSAURUS*: A STUDY IN PALEODETECTIVE PARTNERSHIPS

BRENT H. BREITHAUPT
Geological Museum, University of Wyoming, Laramie, WY 82071

ABSTRACT—The Late Jurassic dinosaur *Allosaurus* has been known for over 100 years. However, it was not until 1991, when "Big Al" was discovered, that one of the most fascinating paleontological mysteries began to unfold. The skeleton was found on public lands administered by the Bureau of Land Management near Shell, Wyoming in the Upper Jurassic Morrison Formation. Research on this specimen has provided exciting new information on *Allosaurus*, the dominant predator of the Late Jurassic of North America), as well as the environment in which it lived. "Big Al"(MOR 693) is a 95% complete, partially articulated, and pathologic (i.e., with broken, fractured, and infected bones) skeleton of a subadult *Allosaurus* fragilis. "Big Al" has gained international recognition, as the scenario of its tragically painful life, early death, and rapid burial has been told through interactive exhibits and state-of-the-art-television programs.

In addition, the intricate tale of this dinosaur's discovery adds intrigue to "Big Al's" story. A short distance to the south and slightly lower stratigraphically from the "Big Al" Quarry, the famous Howe Quarry was worked by crews from the American Museum of Natural History in the 1930s. Over the years, hundreds of people, including teams from the American Museum of Natural History, walked right over "Big Al," still buried in the rock. The discovery of this dinosaur exemplifies the fact that significant paleontological material remains to be discovered in the Rocky Mountain West. Interagency cooperation is essential to collect, study, interpret, exhibit, and preserve these specimens for future generations. The "Big Al" project serves as a model of such cooperation. As it involved scientists, students, volunteers, land managers, educators, media, local museums, and the general public, it is an excellent example of a "paleodetective" partnership.

ALLOSAURUS

The carnivorous dinosaur *Allosaurus* has been known since the late 1800s. This theropod was first documented in 1869, when Ferdinand Vandiveer Hayden was presented with a "petrified horse hoof" by locals in the Middle Park region of Colorado (Hayden, 1869). This specimen of a fragmented, caudal vertebra was identified by Joseph Leidy (1870) as belonging to the European dinosaur genus *Poicilopleuron*. Later Leidy (1873) suggested that this specimen may represent a new genus, *Antrodemus*. Several years later, remains of this type of theropod were found when additional caudal vertebrae, as well as a variety of other elements (i.e., dorsal vertebrae, phalanx, tooth, and humerus) and a separate, partial skeleton were uncovered in the Garden Park area of Colorado. This material (more diagnostic than the earlier finds) was described by Othniel Charles Marsh (1877) as representing a new taxon of theropod dinosaur, *Allosaurus fragilis*. Since the 1870s, thousands of *Allosaurus* specimens representing individuals of different ages have been recovered in exposures of the Morrison Formation in the Rocky Mountain West (Gilmore, 1920; Madsen, 1976; Bilbey, 1999).

Allosaurus fragilis meaning "fragile, different reptile" lived approximately 145-150 million years ago during the Late Jurassic Period, with a recorded geographic range in Wyoming, Montana, Colorado, New Mexico, South Dakota, Utah, Oklahoma and Portugal (Glut, 1997; Prez-Moreno and Chure, 1999). It is known to reach 12 meters in length, 4.5 meters in height, and may have weighed up to 2 tons as an adult. A. fragilis was one of the top predators of its time and is found primarily in the Morrison Formation. It lived on the lowland floodplains of the Western Interior in an environment similar to some of the large plains of Africa today (Russell, 1989) *Allosaurus* was the most common large carnivore of the Late Jurassic in North America. Strong forelimbs with sharp claws, powerful hind legs and recurved, dagger-like teeth are evidence that *Allosaurus* was a formidable predator. During the Late Jurassic, herds of plant-eating sauropods (such as Apatosaurus) were constantly on the move in search of food to satisfy their large appetites. Predators, such as *Allosaurus*, may have followed these herds, preying on the young and weak. Although it was much smaller than the sauropods, quite possibly *Allosaurus* hunted in packs to bring down larger prey. Like many meat eaters, it may also have been a scavenger.

MORRISON FORMATION

A unique deposit, the lithologically variable Morrison Formation represents a 1.5 million square kilometer "sedimentary sheet" extending 1500 kilometers from New Mexico to Canada and 1000 kilometers from Idaho to Nebraska with major fossiliferous outcrops in Wyoming, Colorado, Utah, Montana, New Mexico, Arizona, and Oklahoma (Russell, 1989). Research on the Morrison Formation, has significantly altered our view of the dramatic diversity of terrestrial life that has existed on our planet during the Late Jurassic Period.

The first major vertebrate paleontological sites in the Morrison Formation were discovered in 1877 in Wyoming and Colorado (Ostrom and McIntosh, 1966; Breithaupt, 1998). Since that time, tens of thousands of fossils and hundreds of skeletons (both partial and complete) have been recovered for institutions throughout the world. Over 125 years of extensive collecting has resulted in one of the world's best known prehistoric terrestrial faunas; ranging from algae, cycads, and bivalves to mammals, pterosaurs, and dinosaurs (Chure et al., 1998). Work within the Morrison Formation has added greatly to our understanding of the "life and times" of the Mesozoic Era, as well as to the development of current collecting and preparation techniques.

The Morrison Formation in the eastern Bighorn Basin of Wyoming consists of approximately 65 meters of fluvial, lacustrine, and aeolian sediments (Swierc and Johnson, 1996). This unit is underlain by the primarily marine, Jurassic Sundance Formation, and overlain by the terrestrial, Early Cretaceous Cloverly Formation. The Morrison Formation within the eastern part of the Bighorn Basin was deposited on a low-relief floodplain over the course of seven million years during Tithonian time (Swierc and Johnson, 1996). The "Big Al" skeleton was found stratigraphically slightly above the primary producing layer of the famous Howe Quarry, and is inferred to be approximately 145 million years old (Swierc and Johnson, 1996). However, stratigraphic work by Turner and Peterson (1999) suggests that the "Big Al" and Howe quarries may be roughly 152 million years old and Kimmeridgian in age.

HOWE QUARRY

In 1932, Barnum Brown was notified of the existence of large bones on the ranch of Mr. Barker Howe. Reconnaissance of the site revealed the promise of an extremely rich quarry in the Morrison Formation. Brown returned to the site outside of Shell, Wyoming in 1934 with a field crew from the American Museum of Natural History. Although only two sauropod skeletons were initially uncovered, by later that summer a veritable disarticulated herd had been discovered. Skeletal remains were crisscrossed and interlocked in a confusing, almost inextricable manner in a clay unit beneath a relatively thick sandstone layer (Bird, 1985; Breithaupt, 1997). For two months, bones were exposed, mapped and viewed by thousands of visitors from around the world. After being mapped and photographed, the specimens were painstakingly removed from the quarry. Over 30 metric tons of bones were collected from the Howe Quarry. Roughly six months after the quarry was opened, the last box of fossils (totaling 144) was loaded on a train bound for New York (Brown, 1935; Colbert, 1968).

The Howe Quarry produced over 4,000 Late Jurassic dinosaur remains. Measuring 14 x 20 meters, the quarry contained one of the densest concentrations of Jurassic dinosaur bones ever found. The assemblage of fossils represented at least 20 different animals. The quarry was dominated by the sauropods *Barosaurus*, *Diplodocus*, *Apatosaurus*, and *Camarasaurus*, although some remains of the ornithopod *Camptosaurus* were found. Only isolated theropod teeth attributable to *Allosaurus* were discovered in the quarry. Most remains were disarticulated, but a number of bones showed some degree of association. The Howe Quarry represents an accumulation of desiccated carcass parts that were washed into a small depression during a times of seasonal flooding (Breithaupt, 1997). In addition to bones and teeth, footprints, skin impressions, and gastroliths have also been found in the Howe Quarry (Brown, 1935; Ayer, 2000).

"BIG AL" QUARRY

In 1990, Siber + Siber, Ltd. (a commercial fossil collecting company from Aathal, Switzerland) reopened the Howe Quarry with plans to uncover more dinosaur bones. The original Howe Quarry was expanded and additional material discovered (Ayer, 2000). However, it was not long until the bones of this fossiliferous lens in the Morrison Formation "played out." The Swiss collectors decided to expand their operations laterally with hopes of finding the Howe Quarry bone layer elsewhere. In 1991, they brought in a backhoe to dig test pits along the slope to the north. A new quarry was soon found and a small bonebed exposed. Test digs continued. Approximately 300 meters north of the Howe Quarry, the backhoe hit sauropod bones at about the same level as the Howe Quarry. As excavation of these bones ensued in August, the collectors encountered some theropod vertebrae slightly above the sauropod remains. As they collected this material, they realized that they had stumbled upon many bones of a carnivorous dinosaur. Theropod dinosaurs are relatively rare and very few theropod remains were found in the Howe Quarry. In addition, careful excavation revealed not a random accumulation of disarticulated bones (as had been found in the Howe Quarry), but a single, nearly complete, articulated skeleton. Following the vertebrae to the head-end of the specimen revealed the glint of black enamel, indicating a tooth, which eventually led to an entire tooth row. Later, the jaws and the entire skull were found. Continued work uncovered other parts of the skeleton (Figure 1). The specimen appeared to be about 6 meters long and preliminary identifications hinted that it might be the rare Jurassic dinosaur *Ceratosaurus*.

As excavation continued on the specimen in September of 1991, the lead collector, Kirby Siber, traveled to the Denver Rock, Mineral, and Fossil Show and is rumored to have proudly described his new discovery. While Kirby was in Denver, a Bureau of Land Management (BLM) crew was flying over the area en route to the nearby forests to check for fires. As they flew over the Howe Quarry they recognized that one of the dirt roads in the area had been dramatically modified. As these road improvements on public lands had not been sanctioned, BLM officials inspected the road. This road had been modified to bring in the heavy equipment used by the Swiss crews for excavating bones at the

FIGURE 1. "Big Al" after it was uncovered by Swiss fossil collector.

Howe Quarry and the test pits to the north. The road led investigators directly to a tarp-covered quarry, where the partially uncovered dinosaur lay. Fortunately, few of the fossilized bones had been removed from the ground. It was clear to those visiting the site that the specimen under the tarp was a dinosaur and an interesting one at that. Checking the land records indicated that this quarry and the small bonebed to the south were on BLM land. The dividing line between private land and that administered by the BLM ran between the Howe Quarry and the new theropod skeleton. Unfortunately for the Swiss team, which had permission to collect on private land at the Howe Quarry, they did not have a permit to collect the fossils on BLM land (Figure 2).

Because vertebrate fossils found on public lands belong to the people of the United States and are managed by government agencies in the best interest of the public, vertebrate fossils (which are public resources) can not be privatized nor collected and sold. Fossils collected by commercial dealers often end up in private collections and are not studied scientifically. As a result, these unique, nonrenewable, educational and scientific resources are sometimes lost to science and the public forever.

The BLM called in investigators to study the possibilities of a potential criminal case (i.e., illegal collecting), surveyors to verify the land status, and paleontologists to examine the specimen. Paleontologists from Montana State University's Museum of the Rockies (MOR), the University of Wyoming (UW) Geological Museum, and the Royal Tyrrell Museum in Canada convened at the site to examine the specimen. Although there had been some preliminary speculation that the specimen might represent the theropod *Ceratosaurus*, it was quickly concluded that the fossil was the better known genus *Allosaurus*. Unlike most previously discovered *Allosaurus* specimens, this one was very well preserved, nearly complete, and in partial articulation. Although some carnosaurs have been found which are over 60 percent complete, allosaurids are usually represented by less complete specimens. This specimen appeared to be a subadult, which added to its importance. The Swiss collectors were asked to stop any further activity on the BLM lands and counseled to work strictly on private lands. Although investigators verified unpermitted collecting activity on BLM lands, the Swiss collectors were not charged with any violation. They were, however, warned to be more careful of the land status in any areas of future work. Surprisingly, the landowners in the area were also unaware of the correct boundary lines until this discovery was investigated.

The next problem, was what to do with a partially exposed specimen of a very important fossil. As the dinosaur was found on federal land, regulations required it to be collected by a qualified paleontological team and put into a recognized federal repository for vertebrate fossils. Although many paleontological museums in the country would be acceptable and the National Museum in Washington, D.C. was

200 FEET IN THE WRONG DIRECTION

Rare dinosaur found in 'wrong' place

FIGURE 2. Billings Gazette newspaper story about the "Big Al" discovery - the highlighting the land status issue (Milstein, 1991).

contacted, it was decided that the specimen should stay in the State of Wyoming and go to the UW Geological Museum. Unfortunately, the author was the sole staff member of that museum at that time and the museum lacked the finances, equipment, and people to undertake such a project. Fortunately, the well-staffed and fully-equipped Museum of Rockies agreed to work with the UW Geological Museum and the BLM to excavate and prepare the specimen with plans to provide a display cast for the UW museum in Laramie (Breithaupt, 1996). After the fossil discovery, the BLM's primary concern was to protect the bones and to make certain that Wyoming citizens would have a chance to see "Big Al." The cooperative effort between BLM and the museums fulfilled both of these objectives.

As the BLM considered this find a very important resource for them to protect and preserve, they provided some of the financial support for the project. Shortly after this decision was made, crews arrived at the site to remove the specimen from the ground. It was September and the specimen was already partially exposed (Figure 3). Therefore it was necessary to get the material out of the ground as soon as possible, prior to the first snows of winter. In essence, the project became a salvage operation and crews needed to work quickly and efficiently. An experienced group of students and staff from the Museum of Rockies worked diligently to remove the bones from the ground, while the author worked to photograph and map the bones as they were exposed (Figure 4). The excavation team used small hand tools (hammers, chisels, awls and brushes) to expose as much of the skeleton as possible. All bones were given field identification numbers and their locations at the site mapped. Roughly eight days after the paleontological crews began working at the site, the specimen was exposed, treated with preservative, "plaster-jacketed" (i.e., bones encased in plaster-soaked burlap wraps, making a hard, protective cast), and removed from the ground. "Big Al" was taken to Bozeman for detailed preparation.

FIGURE 3. Overview of the "Big Al" Quarry looking to the east.

As the work progressed, crews undertook an unusual approach to dinosaur excavation; the media and public were actively encouraged to visit the site. With the help of the BLM and public affairs people at the Museum of the Rockies, newspaper and television reporters visited the site. Schools in the Bighorn Basin were closed for part of a day to allow field trips to the "Big Al" Quarry. Over 4,000 students visited the site during the course of the excavation. In addition, BLM officials from around the country, including the Director from Washington, D.C. visited the site. As the stories appeared in newspapers and on CNN around the world, people flocked to the quarry, to see the excavation of the most complete dinosaur skeleton ever found in Wyoming. Thousands of people visited the "Big Al" Quarry and field crews coordinated their efforts to provide interpretation of the site to all that visited (Figure5). With careful planning, the excavation continued unimpeded by the throngs of people watching as the bones were removed from the ground. The BLM also provided law enforcement protection of the site and helped limit after hours visitation. This coordinated effort was one of the most intensive dinosaur excavation, research, and public interpretation endeavors ever undertaken in the field. Because of the careful planning, coordination of efforts, and excellent team work, the project ran smoothly from beginning to end.

Over the course of the next two years, MOR crews returned to the site and removed additional bones of this Allosaurus. These bones were also mapped and included on the map of the quarry (Figure 6). Eventually, nearly all of this theropod was recovered from the site. Although originally called the Siber Quarry, this site was renamed the "Big Al" Quarry and the skeleton nicknamed "Big Al." It was understood that "Big Al" was a small individual measuring roughly only 8 meters, and as such was only 60-70% of its maximum size. However, it was a very "big" find because of its completeness, preservation, and scientific importance.

Once in the preparation lab at the Museum of the Rockies, the bones were carefully removed from the rock and plaster jackets. Delicate cleaning tools including brushes, files and compressed air devices were used to uncover fossil bones (Figure 7). Preservatives were applied to the fossil surface and the cracks were filled to increase the bones' strength. As the bones were carefully prepared, reconstructed, and preserved, it became apparent that about 95% of the specimen had been found. In addition, the skull was the most complete and best preserved *Allosaurus* skull ever discovered (Figure 8). Detailed observation of the bones also revealed that there were a number of interesting abnormalities. Closer inspection indicated these resulted from injuries sustained in life by this *Allosaurus*. Rebecca (Laws) Hanna studied this specimen and described 19 pathologic bones; more known

FIGURES 4a - 4d. Museum of the Rockies and University of Wyoming Geological Museum team working at the "Big Al" Quarry. 4a, Allison Gentry and the author locating bones on the quarry map. 4b, MSU student Greg Erickson excavating vertebrae. 4c, Museum of the Rockies crew working in the "Big Al" Quarry. 4d, Excavation of "Big Al" by Allison Gentry and MSU student Yoshi Tomida. Photos 4a, b, and d by MOR photographer Bruce Selyem.

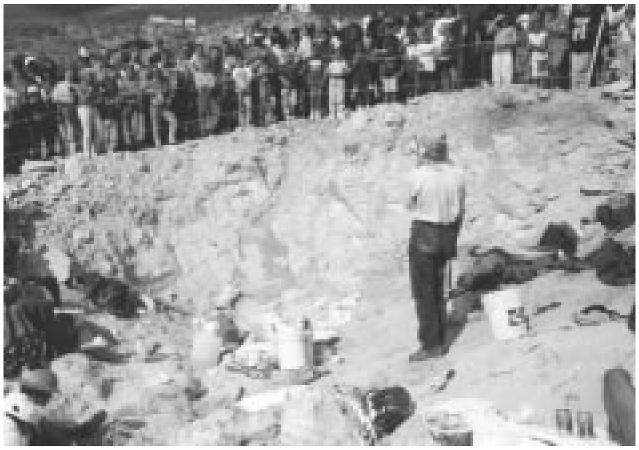


FIGURE 5. The author describing the "Big Al" excavation to school children in 1991. Photo by MOR photographer Bruce Selyem.

than from any other *Allosaurus* (Laws, 1996). These injuries were found throughout the body.

As additional bones were being prepared from the rock, each bone was examined for abnormalities and any information that could be provided about the life, death, and preservation of this dinosaur. In addition, each bone was molded and cast by the MOR. After polyurethane copies were made of the numerous bones of this animal, they were painstakingly painted and put in place in a lifelike skeletal mount of this animal. With the development of new resins in recent years, using casts instead of the actual fossils is a popular way for museums to create dinosaur displays. The casts are much lighter and easier to manipulate, creating much more interesting and lifelike poses. An important consideration is that by using a cast instead of the original fossil, scientists can continue to study actual fossils while the public enjoys the display cast.

In 1995, the cast was completed and stood in the vertebrate paleontology lab at the Museum of the Rockies (Figure 9). Immediately after the cast was assembled, the author went to Bozeman to oversee the disassembly, packing and transportation of the cast to Laramie. Robert Harmon (MOR chief preparator of paleontology), UW students, and the author reassembled this specimen in the exhibit hall at the UW Geological Museum (Figure 10) tail-to-tail with its Jurassic contemporary, *Apatosaurus*. For the first time in 145 million years "Big Al" again stood in Wyoming (in a fashion) in December, 1995. The dedication of this cast and the celebration of the end of the first phase of this project occurred in January, 1996.

However, the "Big Al" project continued. A variety of interpretive and education displays were developed associated with this *Allosaurus* by the UW Geological Museum. Over the course of the next several years, plans were made and materials amassed for the second phase of the "Big Al" project. In 1999 private donors (especially, Al Wolfe and J. David Love) and the BLM provided funding for a series of

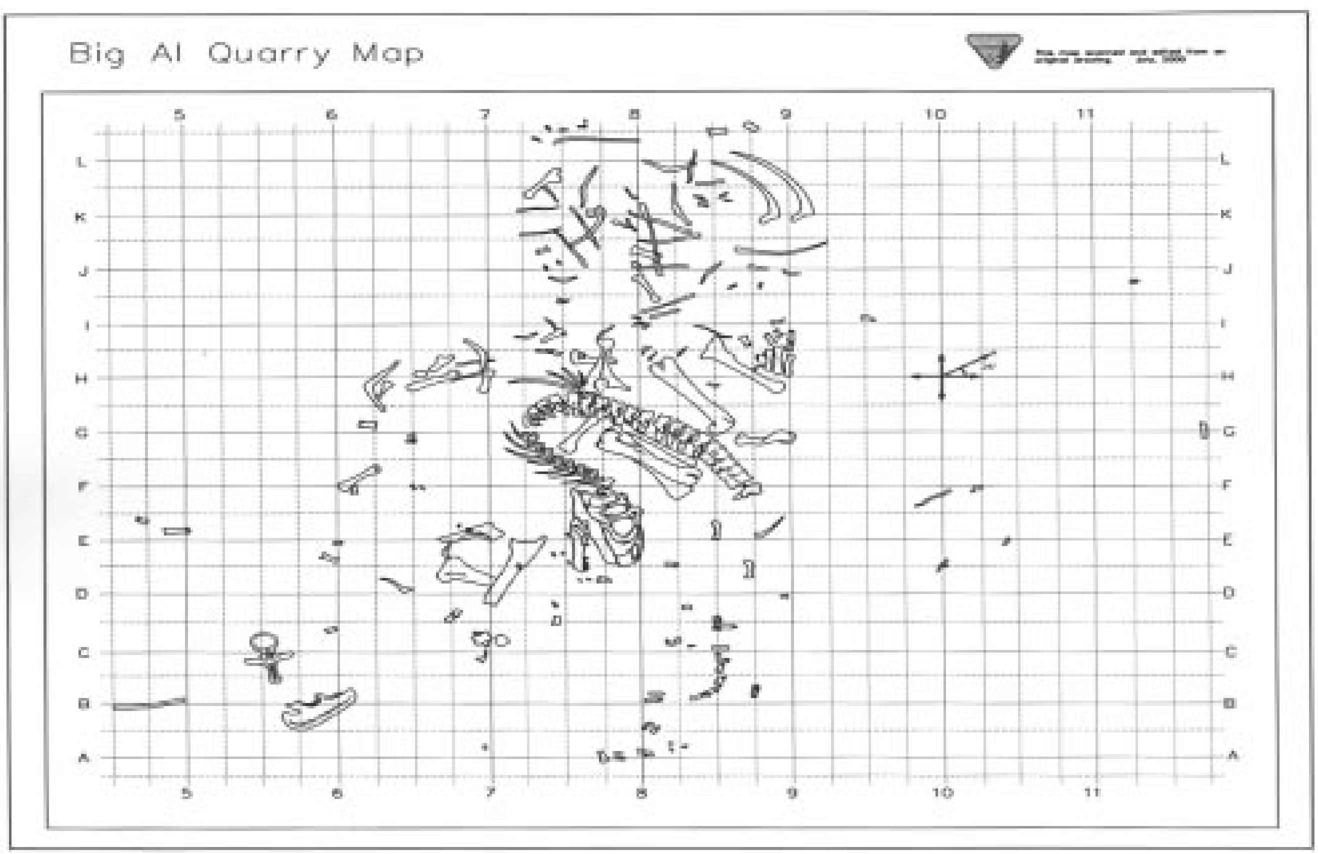


FIGURE 6. "Big Al" Quarry map. Author's original field map redrafted by UW student Scott Hartmon and National Science and Technology Center photogrammetrist Neffra Matthews and cartographer Paul Graves.

FIGURE 7. Preparation of "Big Al" skeleton at the Museum of the Rockies by Bob Harmon. Photo by MOR photographer Bruce Selyem.

exhibits interpreting "Big Al's" life. The museum hired students, commissioned artists, and accumulated a variety of casts to tell a unique story about this dinosaur. In 2001, the displays on this specimen will be unveiled to the public.

The "Big Al" exhibit will become a highlight display at the UW Geological Museum. The exhibit is planned to be one of the most comprehensive displays on *Allosaurus* anywhere in the world. The history of discoveries of Allosaurus in the Rocky Mountain West will be told, ranging from the 1869 discovery of the single fragment of a tail bone to the nearly complete skeleton of "Big Al" in 1991. Interactive displays will teach the museum visitor about the process of scientific investigation. An educational exercise (What Killed "Big Al"?: Investigating the Evidence) is also being developed. This exercise will be utilized by Kindergarten - College age students that visit the museum. The displays will engage the students to think like scientists, gather data and make appropriate interpretations. Tens of thousands of visitors (including thousands of students) from around the world visit the museum each year. Eventually, this exercise will be put on the museum's website (http://www.uwyo.edu/geomuseum/) so that students unable to visit the museum can still learn from the exhibit.

While the UW Geological Museum developed displays and educational programs around the cast of "Big Al," a team of "paleodetectives" was studying the original fossil bones of this dinosaur. Rebecca (Laws) Hanna continued her work on the pathologies of "Big Al" (Laws, 1996; Hanna, 2000; Hanna, in press). Dan Chure incorporated the important osteological features of this dinosaur into his doctoral dissertation work on *Allosaurus* (Chure 2000). Paul Bybee (1996) utilized this specimen in his dissertation growth study on *Allosaurus*. John Foster and Chure included "Big Al" in their hind limb proportion allometric study on Allosaurus (Foster and Chure, 1999). Recently, Cambridge paleontologist Emily Rayfield CT scanned the skull of "Big Al" to determine the cranial biomechanics of its skull (Rayfield et al, 2001). A study which she will also incorporate into her doctoral dissertation. Taphonomic studies dealing with ancient beetle traces on dinosaur bones have also included "Big Al's" skeleton (Laws et al., 1996; Hasiotis et al., 1999). Building on his photodocumentation and mapping work, the author continues his taphonomic analysis of the specimen. As "Big Al" is one of the most complete *Allosaurus* specimens ever discovered and is stored accessibly in a federal repository, it will continue to provide paleontologists around the world with exciting investigative opportunities. The Museum of the Rockies cast a second "Big Al" mount for their highly acclaimed traveling exhibit "*T. rex* on Trial." As numerous presentations were given on this specimen, "Big Al" became the focus of media attention around the world. In a case of serendipity, as the displays were being developed at the UW Geological Museum, the British Broadcasting Corporation (BBC) contacted the museum with plans to do a special high-

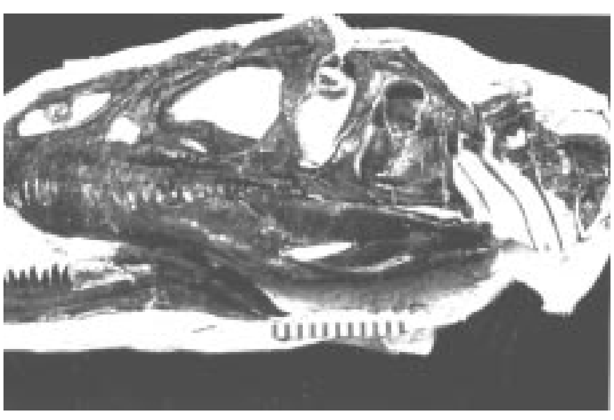


FIGURE 8. The left side of "Big Al" skull as it was being prepared out from the surrounding rock while still in its protective plaster jacket. Photo by Bruce Selyem.

FIGURE 9. Bob Harmon with "Big Al's" skeletal cast at the Museum of the Rockies, Montana State University. Photo by Bruce Selyem.

lighting "Big Al," as part of their hugely successful "Walking with Dinosaurs" series. BBC's "The Ballad of "Big Al'" aired in Europe and Australia in December 2000 and in the United States in April 2001 (Salamon, 2001). "Big Al" continues to be known worldwide, as the UW mount is seen by people on a variety of websites currently available (e.g., BBC, Discovery Channel, UW Geological Museum). Continued projects, exhibits, research, and education activities will proceed on this unique specimen for years to come (Leiggi and Breithaupt, in press).

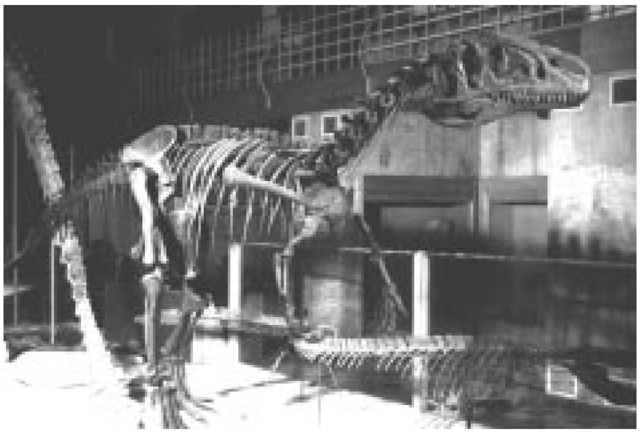


FIGURE 10. "Big Al's" skeletal cast at the University of Wyoming Geology Museum. Photo by Ted Brummond.

STORY OF "BIG AL'S" LIFE AND DEATH

After nearly a decade of "paleodetective" investigative work on this specimen, the story of "Big Al" is finally coming to light. The interpreted scenario of the final days of "Big Al's" life, its death, and subsequent burial are as follows. A young (subadult) Allosaurus of indeterminate gender, approximately 60-70% of its adult size, struggled to survive on a floodplain of what is now northern Wyoming approximately 145 million years ago. Its exact age is difficult to determine, as the physiology and growth rates of dinosaurs are still under study. Individual specimens like "Big Al" may provide important clues on these topics, as bone histology studies are done. Paul Bybee (personal communication) has speculated that "Big Al" was no more than 7 years old. However, this author feels that it was probably older. Interestingly, *Allosaurus* is the only allosaurid genus represented by immature specimens, as well as adults.

Wyoming's environment 145 million years ago was experiencing dramatic wet and dry seasons. During the dry season, the struggle for survival was increased as "Big Al" had to obtain food and water. It was a young animal and many of its prey were much larger. Smaller prey were quick and some could put up a considerable fight. Complicating "Big Al's" struggle were the many injuries that this dinosaur suffered. Although the causes of these injuries are unknown, the complications of such pathologies can be correlated with similar abnormalities seen in modern animals. Continued study on these pathologies may lend some important insights

FIGURE 11. "Big Al's" pathologic right ribs.

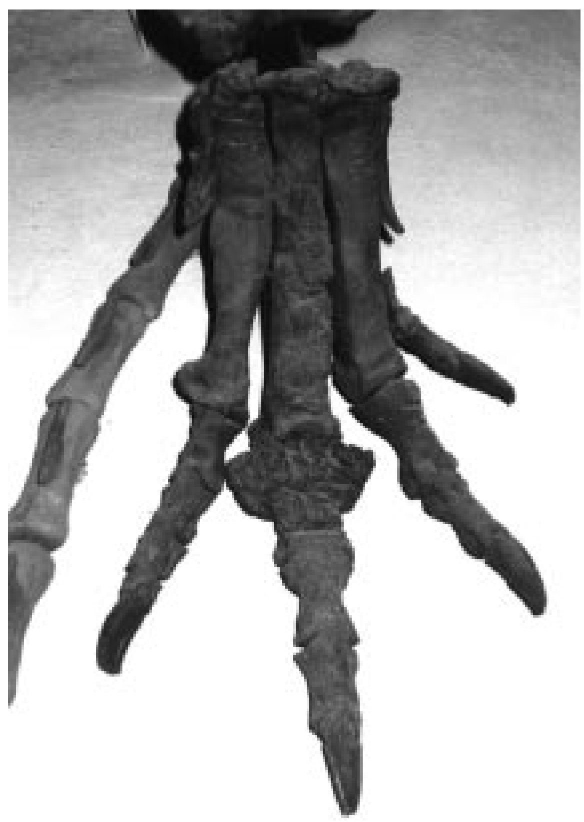


FIGURE 12. "Big Al's" pathologic right foot.

into dinosaur behavior. Were these injuries inflicted from some interspecific battle with prey animals like *Apatosaurus*, *Barosaurus*, or *Stegosaurus*? Were they the cause of some intraspecific fight with another Allosaurus over food, pack hierarchy, or mating? Or was this *Allosaurus* a clumsy, diseased individual who injured itself as it stepped or fell on sharp rocks and logs? "Big Al" assuredly had numerous injuries to its soft tissue (i.e., skin and muscle), as well. Various fractures, breaks, infections, and intergrowths in "Big Al's" foot, tail, hand, ribs (Figure 11), hips, back, and arm dramatically affected its effectiveness as a predator. Thus, hunting would have been difficult. Undoubtedly, it was a weaker, less efficient predatory dinosaur than its healthy contemporaries. Although no one injury may have caused "Big Al's" premature death (although a systemic infection could be fatal), the combination of all of these injuries and those not preserved osteologically may have been the ultimate cause of "Big Al's" demise, as it struggled to find food and water during the dry season. "Big Al's" infected toe bone (which preserves a major open abscess) is unquestionably one of its most painful injuries. This pathology on the major weight bearing toe (Figure 12) would have made walking very painful and may have resulted in "Big Al" limping.

As "Big Al" struggled to find food and water, it collapsed in a dry river bed (Figure 13), leading to its rapid envelopment by sand and mud. The completeness of the specimen indicates that the carcass was not transported very far from where the animal expired, representing essentially an autochthonous deposit. As "Big Al" lay in the dry stream bed, its carcass desiccated in the hot sun. The muscles, tendons, and other soft tissue dried, and the animal's head pulled back over its tail in a characteristic "death pose"(opisthotonic body position) often seen in articulated fossil vertebrates in arid environments (Weigelt, 1989). Because "Big Al's" preserved skeleton still had many of its bones in articulation, this carcass was buried soon after death, prior to the soft tissue completely decaying away. Once buried, decay of the remaining soft tissue continued, but the bones remained locked in life position by the entombing sediments. The beautiful preservation of the bones of the left side of "Big Al" (i.e., limb, hip, and skull) indicates that as this dinosaur lay on its left side, partially buried in sand soon after death. Perhaps this initial burial was by sediment laden flood waters associated with the start of the rainy season. "Big Al's" corpse may have been anchored from additional stream transport by its left limb, which was buried first and embedded into the sediment. Although the left side of the carcass was quickly engulfed with sediment, the right side remained exposed. As the soft tissue decayed away the bones began to disassociate. The right leg was moved by current action anterodorsally to the dorsal vertebrae and buried on the left side of the specimen. The femur, tibia, and fibula remained in association, as the ligaments have not completely decayed. The right ilium was disassociated from the hip region and transported several meters laterally. Whereas the left side of the skull was well embedded in the sediment, the right side of the skull was exposed longer, as indicated by the scattering of maxillary teeth and the disarticulation of the lower jaw. The specimen was lying on its left side with its ventral portion slightly tilted upward, probably associated with bloating of the body cavity. This body position allowed for the ischia and associated pubes to be disarticulated from the hip region and moved anteriorly along the axial skeleton. Many of the ribs and gastralia and other smaller elements (e.g., hand and foot bones) were found disarticulated and scattered primarily ventral to the axial skeleton. The scatter pattern of these elements indicates that they may have been disassociated and transported a short distance due to an eddy current caused by "Big Al's" axial skeleton during later flooding events. Although speculative, it is possible that there was some scavenging on the internal organs of this animal. This activity could scatter some of the chest region without showing any visible effect on the bones themselves. Although there is little evidence of vertebrate scavenging on "Big Al's" bones, close inspection of the bones shows the evidence of beetle burrows on some of the elements, suggesting that "Big Al's" carcass was the "dining spot" of hundreds to thousands of beetle larvae (Laws et al., 1996; Hasiotis et al., 1999). Within a half a year after death, "Big Al" was most likely buried completely by sands and muds. The pattern of "Big Al's" skeletal elements indicates that it was buried by a series of flooding events over the course of many weeks. These flood waters contained high quantities of sediment and a few disassociated sauropod bones that were deposited around "Big Al's" skeleton.

CONCLUSION

In 1991, a partially articulated skeleton of a sub-adult *Allosaurus* was discovered near Shell, Wyoming in the Upper Jurassic Morrison Formation. This area of northern Wyoming has been known to contain important dinosaur remains ever since crews from the American Museum of Natural History in New York collected there in the 1930s. In August of that year, a nearly complete (95%), partially articulated, subadult, *Allosaurus fragilis* (with at least 19 pathologic bones) was uncovered just north of the Howe Quarry. This specimen, nicknamed "Big Al," is beautifully preserved and one of the most complete skeletons of *Allosaurus* ever discovered. Found on public lands administered by the BLM, the specimen has been studied by scientists from around the world. Research by these "paleodetectives" has unearthed important clues about this specimen and the area in which it lived, as well as providing valuable information on the life and times of Jurassic carnosaurs. An important find, such as this *Allosaurus*, indicates that significant paleontological material continues to be uncovered in the Rocky Mountain West even after 150 years of discoveries (Breithaupt, 1999). With a high potential for new discoveries to be made in this region, interagency cooperation (to share expertise and resources) is essential to collect, study, interpret, exhibit, and preserve these specimens for future generations.

The excellent cooperation exercised by the various groups and individuals involved with the "Big Al" project allowed for the efficient extraction of the skeleton from the

FIGURE 13. "Big Al" dying in a river channel. Drawing by UW student Thomas Adams.

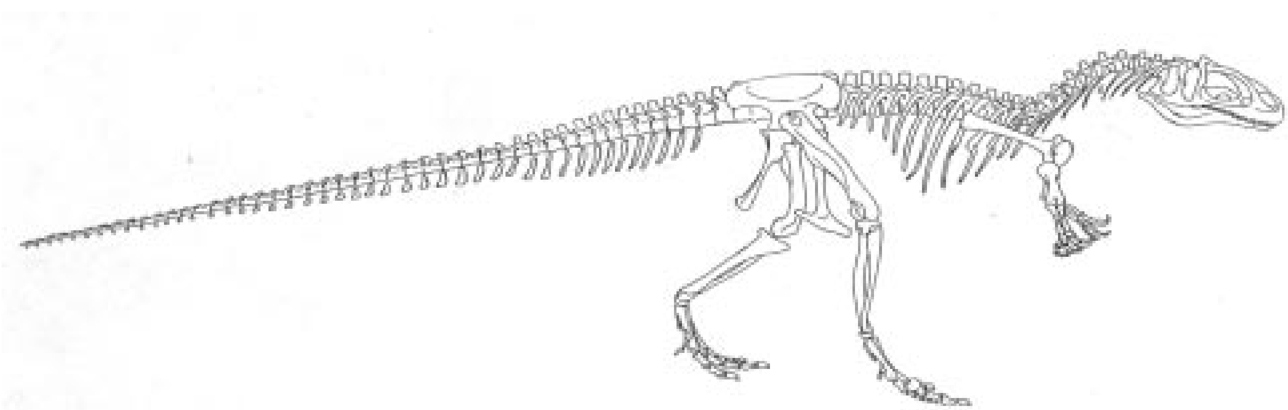


FIGURE 14. Skeletal reconstruction of "Big Al". Drawing by UW student Thomas Adams.

ground. The safeguarding of natural scientific resources, such as this *Allosaurus*, indicates a realization that fossils have a fascinating story to tell us about past life and environments and is a role model for future paleontology projects. It is hoped that this type of "paleodetective" partnership project will be emulated by other land management agencies and paleontologists in the future.

ACKNOWLEDGMENTS

Appreciation is extended to the students, volunteers, staff, collectors, and researchers who were all "paleodetectives" in the unearthing and understanding of this dinosaur. Gratitude is extended to various BLM representatives, especially those of the Cody Office, for their help in arranging and participating in this project. Thanks to BLM paleontologist Laurie Bryant for her assistance in the project. Thanks goes out to the BLM for assistance in funding various parts of this study. Various reviewers provided valuable suggestions on this manuscript. Most importantly, a thanks to my colleagues at the Museum of Rockies in Montana, especially Pat Leiggi, Shelley McKamey, Bob Harmon, Allison Gentry, Karen Masta, Ellen Lamm, Carrie Ancell, and Jack Horner for spear-heading this cooperative project to preserve and protect this important scientific and educational resource.

REFERENCES

AYER, J. SAURIERMUSEUM AATHAL, 2000. The Howe Ranch dinosaurs, Aathal, Switzerland, 96 p.

BILBEY, S. A., 1999. Taphonomy of the Clevelend-Lloyd Dinosaur Quarry in the Morrison Formation central Utah - A lethal spring-fed pond, *in* Gillette, D. D. (ed.), Vertebrate paleontology in Utah, Utah Geological Survey, Miscellaneous Publication 99-1, p. 121-133.

BIRD, R. T., 1985. Bones for Barnum Brown: adventures of a dinosaur hunter: Texas Christian University Press, Fort Worth, 225 p.

BREITHAUPT, B. H., 1996. The discovery of a nearly complete *Allosaurus* from the Jurassic Morrison Formation, eastern Bighorn Basin, Wyoming, *in* Bowen, C.E., Kirkwood, S.C., and Miller, T.S. (eds.), Resources of the Bighorn Basin: Forty-seventh Annual Field Conference, Guidebook, Wyoming Geological Association, Casper, p. 309-313.

_______, 1997. Howe Quarry, in Currie, P.J. and Padian, K. (eds.), Encyclopedia of dinosaurs, Academic Press, San Diego, p. 355-356.

_______, 1998. Railroads, blizzards, and dinosaurs: A history of collecting in the Morrison Formation of Wyoming during the Nineteenth Century, *in* Carpenter, K., Chure, D.J., and Kirkland., J.I. (eds.), The Upper Jurassic Morrison Formation: An interdisciplinary study, Part 2, Modern Geology, v. 23, p 441-463.

_______, 1999. The first discoveries of dinosaurs in the American West, *in* Gillette, D.D., (ed.), Vertebrate paleontology in Utah, Utah Geological Survey, Miscellaneous Publication 99-1, p. 59-65.

BROWN, B., 1935. Sinclair dinosaur expedition, 1934, Natural History, no. 36, p. 3-13.

BYBEE, P.J., 1996. Histological bone structure differences in various sized elements from the Late Jurassic dinosaur *Allosaurus fragilis* of central Utah. PhD dissertation, Brigham Young University, Provo, Utah, 200 p.

CHURE, D.J., 2000. A New Species of *Allosaurus* from the Morrison Formation of Dinosaur National Monument (UT-CO) and a Revision of the Theropod Family Allosauridae. PhD dissertation, Columbia University, New York, 964 p.

CHURE, D.J., CARPENTER, K., LITWIN, R., HASIOTIS, S., AND EVANOFF, E., 1998. Appendix. The fauna and flora of the Morrison Formation, *in* Carpenter, K., Chure, D.,J., and Kirkland., J.I. (eds), The Upper Jurassic Morrison Formation: An interdisciplinary study, Part 2, Modern Geology, v. 23, p. 507-537.

COLBERT, E.H., 1968. Men and dinosaurs, E. P. Dutton and Co., Inc., New York, 283 p.

FOSTER, J.R. AND CHURE, D.J., 1999. Hindlimb proportion allometry in juvenile to adult *Allosaurus* (Dinosauria, Theropoda) (Abstract): Journal of Vertebrate Paleontology, v. 19 (3), p. 45A.

GILMORE, C.H., 1920. Osteology of the carnivorous Dinosauria in the United States National Museum, with special reference to the genera *Antrodemus* (*Allosaurus*) and Cerato*saurus*: Smithsonian Institution, United States National Museum, Bulletin 110, p. 1-159.

GLUT, D.F., 1997. Dinosaurs: The encyclopedia, McFarland & Company, Inc., Jefferson, North Carolina, 1076 p.

HANNA, R.R., 2000. Dinosaurs got hurt too, *in* Paul, G. (ed.), The Scientific American Book of Dinosaurs, St. Martin's Press, New York, p 119-126.

______, (in press). Multiple injury and infection in a subadult theropod dinosaur *Allosaurus fragilis* with comparisons to allosaur pathology in the Cleveland-Lloyd Collection, Journal of Vertebrate Paleontology.

HASIOTIS, S.T., A.R. FIORILLO, AND R.R. HANNA, 1999. Preliminary report on borings in Jurassic dinosaur bones: Evidence for invertebrate-vertebrate interactions, *in* Gillette, D.D. (ed.) Vertebrate paleontology in Utah, Utah Geological Survey, Miscellaneous Publication 99-1, p. 193-200.

HAYDEN, F.V., 1869. Third Annual Report of the United States Geological Survey of the Territories embracing Colorado and New Mexico, *in* Hayden, F.V. (geologist-in-charge), 1873, 1st, 2nd, and 3rd Annual Reports of the United States Geological Survey of the Territories for the years 1867,1868, 1869, Department of the Interior, Government Printing Office, Washington, p. 103-251.

LAWS, R.R., 1996. Paleopathological analysis of a sub-adult *Allosaurus fragilis* (MOR 693) from the Upper Jurassic Morrison Formation with multiple injuries and infections. Masters Thesis, Montana State University, Bozeman, Montana, 61 p.

LAWS, R.R., S,T, HASIOTIS, A.R. FIORILLO, D.J. CHURE, B.H. BREITHAUPT, AND J.R. HORNER, 1996. The demise of a Jurassic Morrison dinosaur after death - Three cheers for the dermestid beetle (Abstract): Geological Society of America Meeting (Denver, Colorado), Abstracts with Programs, v. 28, no. 7, p. A-299.

LEIGGI, P. AND B.H. BREITHAUPT, (in press). The story of "Big Al": the world's most complete *Allosaurus*, Geological Survey of Wyoming, 40 p.

LEIDY, J., 1870. (Proposal of *Poicilopleuron valens*), Proceedings of the Academy of Natural Science in Philadelphia, v. 22, p. 3-4.

______, 1873. (Proposal of *Antrodemus valens*), Contributions to the extinct vertebrate fauna of the western territories: Report of the U. S. Geological Survey of the Territories, i, p. 14-358.

MADSEN, J.H., 1976. *Allosaurus fragilis*: a revised osteology: Utah Geological and Mineral Survey, Bulletin 109,

p. 1-163.

Marsh, O.C., 1877. Notice of new dinosaurian reptiles from the Jurassic formation. American Journal of Science 3(14) p. 513-514.

Milstein, M., 1991. Rare dinosaur found in 'wrong' place: Billings Gazette, September 19.

Ostrom, J.H. and J.S. McIntosh, 1966. Marsh's dinosaurs, Yale University Press, New Haven, 388 p.

Prez-Moreno, B.P. and D.J. Chure, 1999. On the presence of *Allosaurus fragilis* (Theropoda: Carnosauria) in the Upper Jurassic of Portugal: first evidence of an intercontinental dinosaur species, Journal of Geological Society of London, v. 156, p. 449-452.

Rayfield, E.J., D.B. Norman, C.C. Horner, J.R. Horner, P.M. Smith, J.J. Thomason, and P. Upchurch, 2001. Cranial design and function in a large theropod dinosaur, Nature, v. 409, p. 1033-1037.

PASSPORT-IN-TIME MICROVERTEBRATE FOSSIL PROJECT AT THE UNIVERSITY OF WYOMING GEOLOGICAL MUSEUM: LATE CRETACEOUS PALEONTOLOGICAL RESOURCES IN THE PUBLIC EYE

BRENT H. BREITHAUPT
Geological Museum, University of Wyoming, Laramie, WY 82071

ABSTRACT—During two weeks in February of 1999, the University of Wyoming Geological Museum conducted a laboratory project working with Late Cretaceous microvertebrate fossils collected from the Lance Formation of the Thunder Basin National Grassland in northeastern Wyoming. This project utilized volunteers under the auspices of the Forest Service's Passport-in-Time (PIT) program. The program at the University of Wyoming was one of the first PIT programs dealing with paleontology on Forest Service lands. The Forest Service and UW Geological Museum established this project to help one another accomplish mutually beneficial objectives related to proper management of paleontological resources on lands administered by the Forest Service. One such objective was to get the public involved with paleontology through participation in scientific research, in hopes of increasing their understanding of the management of fossil resources on federal lands. Lance Formation microvertebrate fossils represent important components of the latest Mesozoic vertebrate faunas of the Western Interior. Two previously unstudied sites were the focus of this project. The participants recognized two very different faunas through screen-washing, sorting, and fossil identification. These Late Cretaceous fossils from the Thunder Basin National Grassland of Wyoming are examples of the paleontological resources that are being studied through the collaborations of scientists, students, volunteers, and land managers. As the public becomes more involved in the scientific process, they gain a better understanding of fossil resources and the importance of studying them. Through programs like PIT, people with different backgrounds are encouraged to become partners in paleontological resource management.

INTRODUCTION

Perhaps now more than ever before, the general public travels to museums to learn about the intriguing beasts of the past and the exciting wonders of our ancient world. They marvel at how our planet has evolved through its 4.5 billion year history and how animals and plants have changed through time. One advantage of the current popularity of dinosaurs is that more people are thinking about paleontology; how it works and how much there is still left to learn. Museums provide an important link between scientists and the public, by translating the information provided by researchers into interesting stories about our past.

In addition to telling the stories of past life, most museums are mandated to protect and preserve the scientific resources in their collections. In addition, museums are entrusted with the responsibility to ensure the protection of these resources, by educating the public about their importance. This means not only discussing current scientific ideas, but also demonstrating the need for protecting this material from activities that could be detrimental to the progress of science. This exchange of information often translates into museum exhibits. Vertebrate fossils are excellent examples of geological resources in need of protection, because of their rarity and unique educational and scientific values. While the "megafauna" is often the focus of public attention, the often overlooked microvertebrate fossils are critical to our understand of ancient ecosystems.

During February 14-19 and 21-26, 1999, the University of Wyoming Geological Museum (with Forest Service participation) conducted an in-house laboratory project working with Late Cretaceous microvertebrate fossils collected from the Lance Formation of the Thunder Basin National Grassland in northeastern Wyoming. This project utilized volunteers under the auspices of the Forest Service's Passport-In-Time program. There were 20 available openings for participants. Those 18 and over were invited to the program, but younger participants were encouraged to attend with a responsible adult. No special skills were required other than an interest in lab work and the ability to look through a microscope for extended periods of time. To facilitate the understanding and participation of the volunteers in the process of microvertebrate analysis of Wyoming's Cretaceous inhabitants, the project focused on laboratory research and activities, including the screen-washing, sorting, and identifying of fossils. The Late Cretaceous Lance Formation microvertebrate fossils represent the little animals that scurried beneath the feet of the late Mesozoic giants.

MUTUAL BENEFITS

The Forest Service and Geological Museum established this project to help one another accomplish mutually beneficial objectives related to the proper management of paleontological resources on Forest Service lands. One such objective was to get the public involved with paleontological research (such as microvertebrate faunal analysis), in hopes of increasing their understanding of the management of fossil resources on federal lands. This project utilized cientifically important fossil-rich samples from Forest Service managed land. The research being conducted is an excellent example of the proper management, utilization, and study of the fossil remains. Furthermore, the public was involved in the scientific process. As a consequence, by becoming partners in paleontological resource management, they acquired a better understanding of the scientific significance of these resources.

In addition, the project's focus on microvertebrate fossils furthers the scientific understanding and management of Lance Formation fossil deposits. Future studies of this material will include the comparison of ancient and modern environments, and will provide additional information for the management of publicly held fossil deposits. This will benefit the Forest Service and is also part of the Geological Museum's mission. As a result, the Forest Service gained valuable information about fossil resources and provided public participation related to the fossils in the Thunder Basin National Grassland.

THUNDER BASIN NATIONAL GRASSLAND

The Thunder Basin National Grassland is managed by the USDA Forest Service as part of the Medicine Bow National Forest. The Thunder Basin National Grassland occupies more than 572,000 acres in a mosaic of state, federal, and private lands totaling over 1.8 million acres. The resources of the Thunder Basin National Grassland, like the National Forests, are managed for a variety of interests and uses. The Forest Service uses the concept of Multiple Use management. The blending of multiple use objectives in a way that conserves and protects the land, while at the same time allowing for the use of its resources, are the basic principles of Multiple Use Management. Currently, livestock grazing, wildlife habitat, mineral production, and recreation are the major uses of these lands. The Grassland, like so many other federal lands, preserves the rich paleontological heritage and fossil diversity of our country, and thus, is a natural national repository of fossil remains.

PASSPORT-IN-TIME PROGRAM

Passport-In-Time (PIT) is a volunteer program of the Forest Service. PIT provides opportunities for individuals and families to work with professional archaeologists, historians, and paleontologists on various research projects. PIT volunteers take part in research on national forests across the nation. Their participation in the PIT program helps in the understanding of the historic and prehistoric stories of North America, as well as assisting in the preservation of the fragile sites that chronicle these stories. PIT participants share in new discoveries, learn about science and research, and meet many new friends. The PIT program provides an important opportunity for the public to contribute to natural heritage resource protection and management. The Passport-In-Time Microvertebrate Fossil Project at the University of Wyoming was one of the first PIT programs to utilize paleontological resources on Forest Service lands.

PALEONTOLOGY PARTNERSHIPS

As Forest Service lands may contain important paleontological resources, paleontology partnerships are an important management tool for the protection of these resources. Fossils on public lands can help document the rich history and diversity of life on our planet. The Forest Service's responsibility for the management and protection of public lands, includes stewardship of its scientific resources. To better protect and manage paleontological resources for present and future generations, the Forest Service works closely with paleontologists at museums and universities to discover, document, and interpret the fossils found on public lands. The fossils in the Thunder Basin National Grassland of Wyoming are examples of the paleontological resources that are being studied through the collaborations of scientists, students, volunteers, and land managers.

LANCE FORMATION

The most prolific unit in Wyoming for Late Cretaceous vertebrate fossils is the Lance Formation (Breithaupt, 1997). It is dominated by nonmarine, coastal floodplain sandstones, mudstones, and marls, with marginal marine sandstones and shales in its lower parts. The latest Cretaceous depositional environment in Wyoming was a warm temperate to subtropical, seasonal floodplain on the west coast of an eastward-regressing inland seaway. The Lance Formation encompasses a fairly short period of geologic time (approximately 1.5 million years) at the end of the Maastrichtian. It reaches over 750 meters in thickness and is found throughout Wyoming. Because of the mammalian fauna found in the Lance Formation, the fossils from this unit are assigned to the Lancian "age" (Russell, 1975; Lillegraven and McKenna, 1986).

The Lance Formation contains one of the best-known Late Cretaceous vertebrate faunas (Archibald, 1996; Estes, 1964; Clemens, 1960, 1963, 1966, 1973; Derstler, 1994; Breithaupt, 1982, 1985; Whitmore, 1985; Whitmore and Martin, 1986; Webb, 1998, 2001). The diverse fauna contains various cartilaginous and bony fishes, frogs, salamanders, champsosaurs, turtles, lizards, snakes, crocodiles, pterosaurs, mammals, birds, and some of the best known Cretaceous dinosaurs (e.g., *Triceratops, Torosaurus, Tyrannosaurus, Edmontosaurus, Pachycephalosaurus, Ankylosaurus, Edmontonia, Thescelosaurus, Troodon, Dromaeosaurus, and Ornithomimus*). Derstler (1994) calculated that 85% of the Lance Formation dinosaurs were represented by the ceratopsian Triceratops, with another 12% of the dinosaur fauna represented by the hadrosaur *Edmontosaurus*. Abundant remains of small vertebrates (e.g., mammals, lizards, and snakes) and ceratopsian dinosaurs were collected for O. C. Marsh by J. B. Hatcher during the years 1889-1894 (Hatcher, 1893; Hatcher et al., 1907). Clemens (1963) provides an excellent summary of investigations done in the Lance Formation of eastern Wyoming.

The physical environment and biotic diversity of the Late Cretaceous of Wyoming is comparable to that seen in the southern United States today. Russell (1989) provides a vivid description of Lancian paleoecology. The subtropical Gulf Coast of the United States is perhaps the best modern correlative to Wyoming's latest Cretaceous landscape. The Gulf Coast has a diverse biota, with a distinctive assemblage consisting of alligators, crocodiles, soft-shelled turtles, sirens, gars, and bowfins, similar to that found in the latest Cretaceous fossil record. The lush lowland vegetation, meandering streams with coastal connections, and areas of occasional ponding with seasonal water restrictions relate closely to the floodplain environments associated with the western epicontinental sea during latest Cretaceous time (Breithaupt, 1982). Knowlton (1922) and Dorf (1942) provide descriptions of the flora of the Lance Formation.

Named for a small drainage (Lance Creek) in the eastern part of Wyoming, the Lance Formation is best known for the exposures found in that region of the Powder River Basin. However, the 1872 discovery of a partial skeleton of a dinosaur from the western part of the state by Drs. F.B. Meek and H.M. Bannister (while working for F.V. Hayden's Geological Survey of the Territories) was the first indication of the paleontological importance of this unit (Breithaupt, 1982; 1994). E.D. Cope (1872) collected and described the material and named a new species of dinosaur, *Agathaumas sylvestris.* Currently, *Agathaumas* is thought to be a form of *Triceratops* (the most common horned dinosaur found in Wyoming and Wyoming's State Dinosaur). Marsh (1889) defined the genus *Triceratops* on material he had originally called *Ceratops horridus* from the Lance Formation of Niobrara County, Wyoming. The type area of the Lance Formation in east-central Wyoming has produced hundreds of *Triceratops* fossils, including at least 100 skulls Derstler, 1994).

Since the discovery of *Agathaumas*, literally tens of thousands of Late Cretaceous vertebrate remains have been recovered from the Lance Formation. Fossil vertebrate material ranging from important microscopic elements to extensive bonebeds, with nearly complete, sometimes articulated dinosaur skeletons, are known. Some of these monospecific bonebeds may contain over 10 bones per square meter (Derstler, 1994). Spectacular specimens like the dinosaur "mummies" (hadrosaur skeletons surrounded by skin impressions) have also been found in the Lance Formation (Lull and Wright, 1942). Carpenter (1982) reported baby dinosaur fossils from this unit from microvertebrate sites. Lockley (personal communication) is studying a fairly diverse tracksite in the Lance Formation.

In addition, the first discoveries of *Tyrannosaurus rex* can be traced to the Lance Formation. In 1892, following one of Hayden's routes into South Dakota, Cope (1892) discovered some vertebral fragments that he named *Manospondylus gigas.* Famed dinosaur hunter Barnum Brown, while exploring the same area of South Dakota and eastern Wyoming, discovered a partial skeleton in 1900. H. F. Osborn (1905) named this specimen *Dynamosaurus imperiosus* ("powerful imperial lizard"). However, earlier in the same paper Osborn also named a second and more complete skeleton of this dinosaur from Montana, *Tyrannosaurus rex* ("king of the tyrant lizards").

PROJECT HISTORY

During the summer of 1994, an archeological survey was conducted for the Forest Service in the Thunder Basin National Grassland in eastern Wyoming. During the course of this inventory, some pieces of fossil bone were discovered in sandstones of the Lance Formation in Weston County. The University of Wyoming (UW) Geological Museum and South Dakota School of Mines and Technology (SDSM) Museum of Geology were contacted. Upon closer inspection, the bones were identified as pieces of the bony plates from an armored dinosaur. The following summer, a crew from the SDSM Museum of Geology returned to the site (SDSM V9523) with the hopes of finding more bones. The summer field program involved a crew made up of students, professors, and members of the general public. The rocks and fossils at the site were thoroughly documented with photos and written notations. Meter grid squares were laid out at the site and were carefully troweled in search of fossil bone. Fortunately, many parts of this dinosaur were recovered, resulting in the first associated partial skeleton of a nodosaurid ankylosaur from eastern Wyoming. Once collected, the specimen was brought to the lab at the SDSM Museum of Geology in Rapid City, where it was prepared, studied, and cataloged (SDSM 34468) by students. Close examination indicated that the specimen represented the armored dinosaur *Edmontonia* (Finlayson, 1997). Several microvertebrate (e.g., multituberculate mammal, garfish, crocodile, turtle, and dinosaur) remains were found near the *Edmontonia* specimen. These were discovered while crawling the weathered sandstone outcrops in search of more bones during a June snowstorm. Additional surveys resulted in several areas of promising exposures from which samples were collected for screen-washing (see Martin and Finlayson, 1997). The screen-wash material was taken to the South Dakota School of Mines and Technology and awaited processing. In 1999, material from two of these sites (i.e., SDSM V9717 - Hoodoo Point Site and SDSM V9718 - Gunsight Ledge Site) was transferred to the UW Geological Museum for use during the Passport-In-Time Microvertebrate Fossil Project. PIT participants took part in standard microvertebrate wet screening washing techniques (Hibbard, 1949; McKenna, 1962; McKenna et al., 1994). Historically, Barnum Brown (1906) was one the first investigators to systematically screen-wash Cretaceous units for microvertebrate fossils.

The indoor screen-washing facility at UW was used to wash the material from the two sites. Samples were placed in screened wash boxes and gently agitated. After the very fine material was washed though the brass screens, the boxes were set outside to dry. Once dried, the Thunder Basin material was concentrated into coffee cans and brought into the museum, where eager PIT volunteers waited to pick through the concentrate. Each PIT participant was provided with his/her own binocular microscope, sorting tools, and microvertebrate identification guide.

While the Thunder Basin Lance Formation material was being washed and dried, PIT participants learned how to sort and identify microvertebrate material from a well-studied Cretaceous site (UW Locality V-81013; Hewitt's Foresight). Worked by individuals from the University of Wyoming for nearly a decade (Breithaupt, 1985; Webb, 1998; 2001), this Lance Formation site from Park County in the northeastern part of Wyoming, is known to contain a tremendously diverse fauna of microvertebrates. Several important mammal specimens were found by the PIT participants for Webb's dissertation.

The Hoodoo Point locality washed best (as it was a weathered, fine-grained mudstone) and the concentrate was relatively easy to microscopically sort. Material from the Gunsight Ledge locality was coarser grained and did not wash as well. As a result, the microscopic sorting of this material was more tedious and provided less frequent results. PIT participants were expected to pick-out all identifiable bones and teeth and categorize the material to the best of their ability. As the project was held within the exhibit hall of the museum, PIT participants became impromptu docents and were quite willing to explain microvertebrate research to regular museum visitors.

The following is the list of fossils discovered by participants in the 1999 Passport-in-Time Microvertebrate Fossil Project at the UW Geological Museum. The number of specimens assigned to each taxon is also listed. Those specimens not identifiable to a particular taxon were not listed.

GUNSIGHT LEDGE (SDSM V9718) MICROVERTEBRATE FAUNA:

Class Chondrichthyes
Order Batoidea
Family Dasyatidae
Myledaphus sp. (6 specimens)

Class Osteichthyes
Infraclass Holostei
Order Lepisosteiformes
Family Lepisosteidae
Atractosteus sp. (45 specimens)

Class Osteichthyes
Unidentified genus and species (33 specimens)

Class Reptilia
Order Sauria
Genus and species understudy (6 specimens)

HOODOO POINT (SDSM V9717) MICROVERTEBRATE FAUNA:

Class Chondrichthyes
Order Selachii
Family Hybodontidae
Lonchidion sp. (4 specimens)

Order Euselachii
Family Orectolobidae
Squatirhina sp. (3 specimens)

Order Batoidea
Family Dasyatidae
Myledaphus sp. (51 specimens)

Class Osteichthyes
Infraclass Chondrostei
Order Acipenseriformes
Family Acipenseridae
Acipenser sp. (7 specimens)

Infraclass Holostei
Order Amiiformes
Family Amiidae
Amia sp. (6 specimens)

Order Lepisosteiformes
Family Lepisosteidae
Atractosteus sp. (3 specimens)

Infraclass Teleostei
Order Perciformes
Family Sciaenidae?
Platacodon sp. (1 specimen)

Class Amphibia
Order Salientia
Family Discoglossidae
Scotiophyrne sp. (3 specimens)

Order Urodela
Suborder Ambystomatoidea
Family Scapherpetonidae
Scapherpeton sp. (3 specimens)

Suborder Proteida
Family Batrachosauroididae
Prodesmodon sp. (2 specimens)

Suborder Meantes
Family Sirenidae
Habrosaurus sp. (2 specimens)

Class Reptilia
Order Sauria
Genus and species understudy (9 specimens)

Order Crocodilia
Suborder Eusuchia
Family Crocodylidae
Leidyosuchus sp. (1 specimen)

Order Saurischia
Suborder Theropoda
Infraorder Coelurosauria
Family Dromaeosauridae
Dromaeosaurus sp. (1 specimen)

Family Saurornithoididae
Paronychodon sp. (1 specimen)

Order Ornithischia
Suborder Ornithopoda
Family Hypsilophodontidae
Thescelosaurus sp. (2 specimens)

Family Hadrosauridae
Edmontosaurus sp. (1 specimen)

Suborder Ceratopsia
Family Ceratopsia
Triceratops sp. (45 specimens)

Class Mammalia
Order Marsupialia
Family Didelphidae
Alphadon sp. (2 specimens)

RESULTS

The Hoodoo Point Site contains a fairly diverse fauna (e.g., bony and cartilaginous fishes, frogs, salamanders, lizards, crocodiles, dinosaurs, and mammals). Many very delicate bones were preserved and subsequently recovered during screen-washing. Material from this site is comparable with that from other Late Cretaceous sites in the Western Interior (Breithaupt, 1982). The taphonomic scenario for the diversity of taxa and preservation of the material are interesting aspects of the Hoodoo Point Site still under investigation. Further collecting at the locality for additional microvertebrates is recommended. The Gunsight Ledge Site has a less diverse fauna, but contains an interesting accumulation of lizard and garfish material. Continued study of this site should prove interesting. The lizard material from both sites is under study.

The specimens from these two sites will be cataloged into the collections at the Museum of Geology, South Dakota School of Mines and Technology (SDSM 47705-48004). As the UW Geological Museum is currently engaged in a number of research projects dealing with latest Cretaceous sites in Wyoming, the material from the Thunder Basin National Grassland will be incorporated into the comparative analyses of lower vertebrate faunas around the State. In addition, the successful public outreach components of this project have been presented to scientists and resource managers in the region.

SUMMARY AND CONCLUSIONS

Since 1872, when the first dinosaur was discovered in western Wyoming, Mesozoic vertebrate fossils have been found throughout the State. Although the biggest boom for Mesozoic paleontology in Wyoming was in the late 1880s, when scientists from the East were collecting for their institutions, paleontologists continue to make important discoveries in Wyoming today. Many of the same collecting practices that were used by paleontologists over 100 years ago are still in practice. Today, fossils from Wyoming's Lance Formation are highlighted in exhibits and research collections in museums throughout the world. Fossil remains range from isolated fragments to complete skeletons.

The paleoecology of the Late Cretaceous of Wyoming is fairly well understood, as a result of over 100 years of study. However, even after more than a century of work, important vertebrate paleontological discoveries are still being made from the Lance Formation in Wyoming. As the potential for new discoveries in the Rocky Mountain West is high, interagency cooperation (to share expertise and resources) is essential to collect, study, interpret, exhibit, and preserve these specimens for future generations. The Passport-In-Time Microvertebrate Fossil Project exemplifies how paleontological resources can be studied through the collaborations of scientists, students, volunteers, and land managers. The program highlights the opportunities for multiple uses of paleontological resources, emphasizing their scientific, educational, interpretive, and recreational values of the fossil record in the documentation of the history of life on earth, which provides a lasting legacy for future generations.

ACKNOWLEDGMENTS

Appreciation is extended to all of the PIT participants who made this project so enjoyable. Thanks to Michael Webb for his help and presentations during the two weeks in February. Gratitude goes out to Thomas Adams for the illustrations used in this report. Michael and Thomas were also both very helpful in the identifying and cataloging of the fossil material. Veronica Sanchez was instrumental in arranging the PIT participants housing on campus. Special thanks go to Forest Service representatives Ian Ritchie, Joe Reddick, Barbara Beasley, and Rusty Dersch for their help in arranging and participating in this project. Beth Southwell and Neffra Matthews provided valuable comments on the manuscript. Various anonymous reviewers also provided valuable suggestions on this manuscript. Finally, thanks goes out to the Forest Service for assistance in funding this program.

REFERENCES

Archibald, J. D., 1996. Dinosaur extinction and the end of an era: Columbia University Press, New York, 237 p.

Breithaupt, B.H., 1982. Paleontology and paleoecology of the Lance Formation (Maastrichtian), east flank of Rock Springs Uplift, Sweetwater County, Wyoming. Contributions to Geology, v. 21, p. 123-151.

________, 1985. Nonmammalian vertebrate faunas from the Late Cretaceous of Wyoming, in Nelson, G. E. (ed.), hirty-sixth Annual Field Conference Guidebook, Wyoming Geological Association, Casper, p. 159-175.

________, 1994. The first dinosaur discovered in Wyoming, in Nelson, G. E. (ed.), Forty-fourth Annual Field onference Guidebook, Wyoming Geological Association, Casper, p. 15-23.

_______, 1997. Lance Formation, in Currie, P. J and Padian K. (eds.), Encyclopedia of dinosaurs, Academic Press, San Diego, p. 394-395.

Brown, B., 1906. Report of expeditions of 1906 to the Montana Laramie, in 1906 Annual Report of the Department of Vertebrate Paleontology, American Museum of Natural History.

Carpenter, K., 1982. Baby dinosaurs from the Late Cretaceous Lance and Hell Creek formations and a description of a new species of theropod, Contributions to Geology, v. 20, no. 2, p. 123-134.

Clemens, W.A., 1960. Stratigraphy of the type Lance Formation, Report of the XXI International Geological Congress (Norden), Part V (Proceedings of Section 3 - The Cretaceous-Tertiary Boundary), p. 7-13.

________, 1963. Fossil mammals of the type Lance Formation, Wyoming. Part I. Introduction and Multituberculata. University of California Publications in Geological Sciences, v. 48, p. 1-105.

________, 1966. Fossil mammals of the type Lance Formation, Wyoming. Part II. Marsupialia. University of California Publications in Geological Sciences, v. 62, p. 1-122.

________, 1973. Fossil mammals of the type Lance Formation, Wyoming. Part III. Eutheria and summary. University of California Publications in Geological Sciences, v. 94, p. 1-102.

Cope, E.D., 1872. On the existence of Dinosauria in the Transition Beds of Wyoming. Proceedings of the American Philosophical Society, v. 12, p. 481-483.

_______, 1892. Fourth note on the Dinosauria of the Laramie. American Naturalist, v. 26, p. 756-758.

Derstler, K., 1994. Dinosaurs of the Lance Formation in eastern Wyoming, in Nelson, G. E. (ed.), Forty-fourth Annual Field Conference Guidebook, Wyoming Geological Association, Casper, p. 127-146.

Dorf, E., 1942. Upper Cretaceous Floras of the Rocky Mountain Region, II, Flora of the Lance Formation at its type locality, Niobrara County, Wyoming: Carnegie Institute of Washington, Publication 508, Contributions to Paleontology, p. 81-168.

Estes, R., 1964. Fossil vertebrates from the Late Cretaceous Lance Formation, eastern Wyoming. University of California Publications in Geological Sciences, v. 49, p. 1-180.

Finlayson, H.C., 1997. The most complete armored dinosaur (Nodosauridae) from the Late Cretaceous (Maastrichtian) Lance Formation of eastern Wyoming (M.S. Thesis): Rapid City, South Dakota, South Dakota School of Mines and Technology 86 p.

Hatcher, J.B., 1893. The Ceratops beds of Converse County, Wyoming, American Journal of Science, series 3, no. 45, p. 135-144.

_______, 1896. Some localities for Laramie mammals and horned dinosaurs, American Naturalist, February 1, p. 112-120.

Hatcher, J.B., O.C. Marsh, and R.S. Lull, 1907. The Ceratopsia: United States Geological Survey Monograph 49, United States Government Printing Office, Washington, 300 p.

Hibbard, C.W., 1949. Techniques of collecting microvertebrate fossils. Contributions of the Museum of Paleontology, University of Michigan, v. 3, no. 2, p. 7-19.

Knowlton, F.H., 1922. The Laramie Flora of the Denver Basin. United States Geological Survey Professional Paper 130, United States Government Printing Office, Washington, 175 p.

Lillegraven, J.A. and M.C. McKenna, 1986. Fossil mammals from the "Mesaverde" Formation (Late Cretaceous, Judithian) of the Bighorn and Wind River basins, Wyoming, with definitions of Late Cretaceous North American land-mammal "ages." American Museum Novitates, no. 2840, p. 1-68.

Lull, R.S. and N.E. Wright, 1942. Hadrosaurian dinosaurs of North America. Geological Society of America Special Paper 40, p. 1-242.

Marsh, O.C. 1889. Notice of gigantic horned Dinosauria from the Cretaceous. American Journal of Science, v. 38, p. 173-175.

Martin, J.E. and H.C. Finlayson, 1997. 1997 paleontological survey of a portion of the Thunder Basin National Grassland, eastern Wyoming: A report to the Medicine Bow National Forest.

McKenna, M.C., 1962. Collecting small fossils by washing and screening, Curator, v. 5, no. 3, p. 221-235.

McKenna, M.C., A.R. Bleefeld, and J.S. Mellett, 1994, Microvertebrate collecting: Large-scale wet sieving for fossil microvertebrates in the field, *in* Leiggi, P. and May, P. (eds.), Vertebrate paleontological techniques: Volume 1, Cambridge University Press, New York, p. 93-111.

Osborn, H.F., 1905. *Tyrannosaurus* and other Cretaceous carnivorous dinosaurs. American Museum of History Bulletin, v. 21, p. 259-265.

Russell, D.A, 1975. Mammalian faunal succession in the Cretaceous System of western North America. *in* The Cretaceous System in the Western Interior of North America, Geological Association of Canada, Special Paper, no. 13, p. 137-161.

Russell, D.A.,1989. An odyssey in time: the dinosaurs of North America, University of Toronto Press, Toronto, 239 p.

Webb, M.W., 1998. A revised summary of Lancian (Latest Cretaceous) mammal localities with introduction to a new Lancian locality (Lance Formation) in the southwestern Bighorn Basin, *in* Keefer, W.R. and Goolsby, J.E. (eds.), Thirty-sixth Annual Field Conference Guidebook, Wyoming Geological Association, Casper, p. 131-136.

_______, 2001. Fluvial architecture and Late Cretaceous mammals of the Lance Formation, southwestern Bighorn Basin, Wyoming, The University of Wyoming, Doctoral Dissertation.

Whitmore, J.L., 1985. Fossil mammals from two sites in the Late Cretaceous Lance Formation in northern Niobrara County, Wyoming, *in* Martin, J. E. (ed.), Fossiliferous Cenozoic deposits of western South Dakota and northwestern Nebraska: Dakoterra, v. 2, p. 353-367.

Whitmore, J.L. and Martin, J.E., 1986. Vertebrate fossils from the Greasewood Creek locality in the Late Cretaceous Lance Formation of Niobrara County, Wyoming: Proceedings of the South Dakota Academy of Science, v. 65, p. 33-50.

INNOVATIVE DOCUMENTATION METHODOLOGIES IN THE STUDY OF THE MOST EXTENSIVE DINOSAUR TRACKSITE IN WYOMING

BRENT H. BREITHAUPT[1], ELIZABETH H. SOUTHWELL[1], THOMAS L. ADAMS[1], AND NEFFRA A. MATTHEWS[2]

[1]Geological Museum, University of Wyoming, Laramie, WY 82071

[2]National Science and Technology Center, Bureau of Land Management, Denver, CO 80225

ABSTRACT—The Red Gulch Dinosaur Tracksite (RGDT) UW V-98066 is a 1600 square meter area of public land administered by the Bureau of Land Management in the eastern Bighorn Basin of northern Wyoming. The most extensive dinosaur tracksite in the State, the RGDT preserves approximately 1000 tridactyl pes imprints in an oolitic limestone interval of the Bathonian (approximately 165 ma) Canyon Springs Member of the Lower Sundance Formation. Arranged into at least 125 discrete trackways, these footprints offer a unique glimpse of Middle Jurassic dinosaur evolution, ecology, and community development. In addition, the RGDT is a significant fossil site due to its extent, geologic age, geographic occurrence, educational opportunities, and public involvement.

To preserve the value of this unique paleontological resource, monitor erosion, and facilitate intensive scientific research of the tracks and trackways, extensive documentation and applications of innovative technologies have been conducted at the Red Gulch Dinosaur Tracksite. Established ichnological field methods consisting of hands-on track identification, ocation, measuring, and detailed recording of the tracks have been utilized over the past 4 years. This documentation is being synthesized with state-of-the-art data collection methodologies, resulting in one of the most precise approaches for the measuring, recording, and evaluating of fossil tracks. Global Positioning Systems data collecting, precision surveying, and photogrammetry were used to facilitate construction of a comprehensive database of information gathered on each track and provide a spatial framework for data analysis. Extensive photographic documentation (including standard format aerial photography, as well as 35-mm photos taken from tripod heights of 2-10 meters, a Low Altitude Remote Controlled plane, an Ultralight aircraft, and a blimp) are being georeferenced with the survey data. As state-of-the-art technology continues to be utilized at this site, the RGDT has gradually become one of the most extensively documented dinosaur tracksites in the world.

INTRODUCTION

Over the past three years, investigations were con ducted on a previously undescribed dinosaur tracksite found in the vicinity of Shell, Wyoming (Figure 1). This tracksite, hereafter referred to as the Red Gulch Dinosaur Tracksite (RGDT), is unique in the State of Wyoming and Represents a significant paleontological resource which will be developed for the educational benefit of the public. The initial tracksite discovery was made on land managed by the Bureau of Land Management (Section 20, T. 52 N., R. 91 W.) in the spring of 1997. Subsequent mapping has extended the tracked layer laterally onto adjacent sections.

After being invited and permitted by the BLM to undertake this study, the investigators devised a plan to study the vertebrate ichnology in this area and to coordinate our findings with those of other researchers working in the region. As this was a previously unrecorded site, the tracks were located, mapped, measured, described, surveyed, photographed and compared with other previously studied track assemblages. Analysis of these data is providing unique insights into individual and group behavior and dynamics, faunal diversity, community structure and habitat of Middle Jurassic dinosaurs in northern Wyoming, as well as the microenvironments of the substrate during track generation and track preservation/erosion. Ultimately, we will be able to tie the Red Gulch Dinosaur Tracksite into a geological and paleontological framework, which will allow comparison of its ichnofauna with other similar trace fossil assemblages worldwide, and to permit correlation of the tracked layer with beds of the same age in Wyoming and elsewhere in the western United States. The proximity of the site to an existing roadway allows for ready access for the public to view the tracks in situ. In a cooperative partnership with the BLM, the investigators have supported development of the site as a unique tool for public education. The investigators have worked with various parties to assist in the creation of interpretive displays and websites, as well as disseminating the information through the media.

PREVIOUS INVESTIGATIONS AND HISTORY

The initial discovery of the Red Gulch Dinosaur Tracksite was in a “dry wash” exposed along the Red Gulch/Alkali Backcountry Byway. The tracks are preserved in a limestone

FIGURE 1. Location map of the Red Gulch Dinosaur Tracksite.

unit in the lower part of the Jurassic Sundance Formation. Although walked and driven over for decades, the dinosaur tracks were overlooked until recently, presumably because the Sundance Formation in the Bighorn Basin has historically been defined as open-water marine in character (Darton, 1899). However, this discovery and other recent work (Kilibarda and Loope, 1997; Schmude, 2000) now demonstrate episodes of subaerial exposure during the Middle Jurassic in this region during regressive phases of the Sundance Sea. In the vicinity of Shell, Wyoming, the lower Sundance strata were deposited on a broad, shallow shelf adjacent to the paleotectonic feature named the Sheridan Arch by Peterson (1957). Schmude (2000) identified another Jurassic paleotectonic feature in this region which he named the Black Mountain High. These local paleohighs created conditions that may have allowed creation and preservation of this paradoxical non-marine dinosaur ichnofauna in an otherwise marine depositional regime. The track-bearing limestone lies stratigraphically below the level of occurrence of the marine invertebrate fossil *Gryphaea nebrascensis* within the lower Sundance Formation. Geologic work in the area has assigned the track-bearing unit to the Middle Jurassic Bathonian age (approximately 165 million years old) Canyon Springs Member of the Sundance Formation (Schmude, 2000).

Any evidence of dinosaur activity from the Middle Jurassic is significant, as this was a period which preserves little terrestrial deposition (particularly in North America), and a very limited, vertebrate fossil record (Shubin and Sues, 1991). Existing dinosaur bone assemblages are relatively sparse from this time, but are known from localities in China, Morocco, Algeria, Madagascar, England, France, Portugal, Argentina, Chile, Australia (Dodson, 1997; Weishampel, 1990) and Mexico (Clark et al., 1994; Fastovsky et al., 1995). The dinosaur track record is also limited. In the New World, existing Middle Jurassic dinosaur track records have been documented from Utah (Lockley and Hunt, 1995; Lockley et al., 1998; Foster et al., 2000), Mexico (Ferrusquia-Villafranca et al., 1996), and Chile (Weishampel, 1990). Worldwide, other Middle Jurassic tracks are reported from England (Whyte and Romano, 1994; Lockley and Meyer, 2000), Scotland, Portugal, Madagascar, Argentina, Morocco, China, and Iran (Lockley and Meyer, 2000), and Australia (Weishampel, 1990). Clues on the existence and nature of dinosaur communities in North America during the Middle Jurassic are especially important and are needed to explain the apparent, sudden explosion of new and abundant faunas that appeared here in the Late Jurassic (Gillette, 1996). The investigators have previously noted that there should be more dinosaur tracks known in Wyoming (Breithaupt, 1994) and have predicted that they would be found with deliberate effort (Southwell and Lockley, 1996). Although vertebrate ichnology studies are in their infancy in Wyoming, dinosaur tracks are known in a variety of units throughout the state (Lockley et al., 1996; Southwell and Breithaupt, 1998; Southwell, Breithaupt, Lockley, and Wright, in prep.). Theropod and sauropod dinosaur tracks and pterosaur tracks have been documented in central Wyoming in the Sundance Formation, and in Utah,

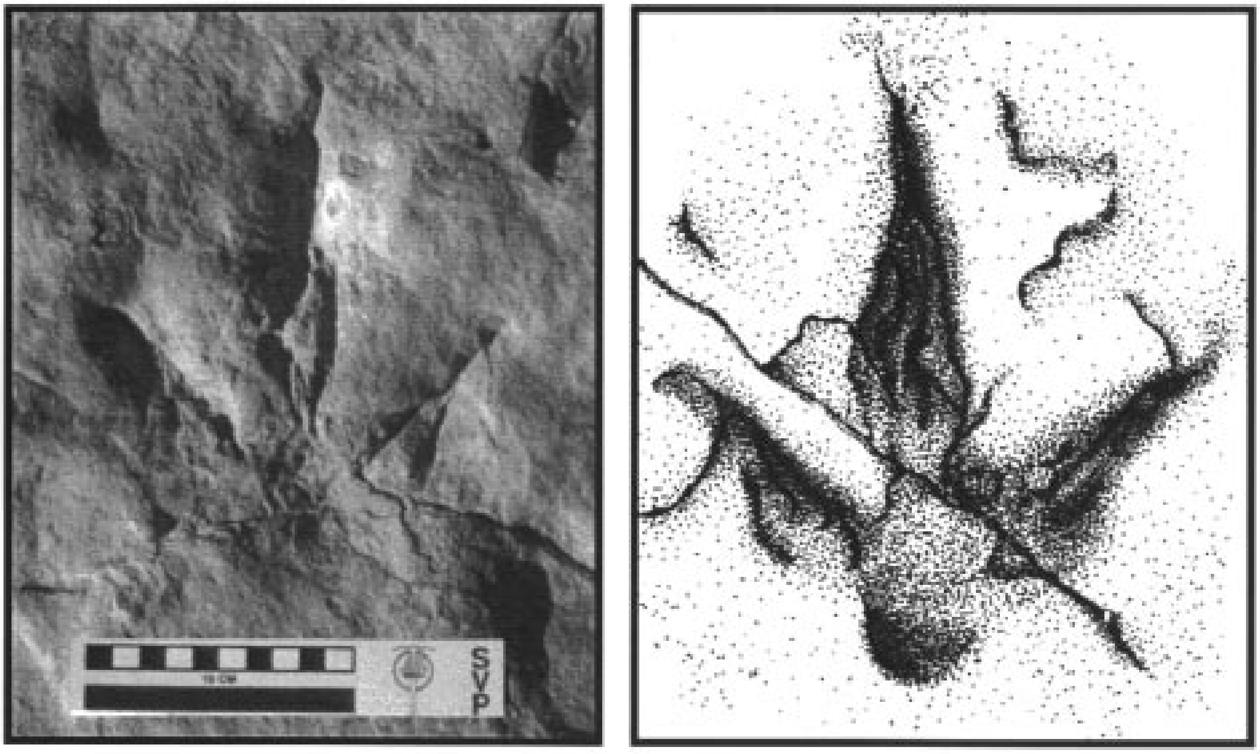


FIGURE 2. Typical Red Gulch Dinosaur Tracksite footprints: phto and sketch. Track drawing by Thomas Adams.

Colorado, Oklahoma, Arizona in the Sundance Formation equivalent Summerville Formation (Lockley et al., 1996). However, these tracks are located in the upper part of the formation and are generally considered to be Late Jurassic.

DESCRIPTION OF THE RED GULCH DINOSAUR TRACKSITE

The Red Gulch Dinosaur Tracksite is a 1600 square meter area designated by the BLM in the eastern Bighorn Basin of northern Wyoming. The RGDT locality is UW V-98066 in the Scientific Collections Database of the Department of Geology and Geophysics at the University of Wyoming. The Smithsonian Institution locality number for the site is USNM Locality 41696. A major arroyo in the 1600 square meter area has been informally broken into 3 distinct areas (i.e., "Corridor," "Ballroom," and "Discovery Area"). Because of the density of tracks, degree of surface exposure, proximity to the road, and BLM development plans, this "dry wash" has been the area of emphasis of study and primary concentration during the past four field seasons.

Dinosaur tracks are preserved as impressions in a gray, ripple-bedded, oolitic, peritidal limestone. This substrate also contains an interesting invertebrate trace fossil assemblage (e.g., Diplocraterion and Rhizocorallium) and various invertebrate body fossils (e.g., pelycypods, gastropods, and crinoids). The majority of tracks (Figure 2) have three distinct digits, a very faint "heel" imprint, sharp claws, and foot lengths greater than widths. This track morphology is consistent with those generally attributed to theropod dinosaurs (Thulborn, 1990). No other types of dinosaurs are currently recognized at the Red Gulch Dinosaur Tracksite based on the documented footprints. However, care must be taken in assigning a trackmaker due to "a rather blurred continuum" (Farlow, 1987) of features shared between theropod and ornithopod trackmakers. In general, assumptions about the identity of specific trackmakers must be approached with caution, unless direct bone evidence can be found and correlated with the tracks (Lockley, 1997). At the RGDT, all of the tracks are tridactyl pes impressions ranging in length from 8-30 cm. Most of the tracks are between 15-21 cm in length. From this evidence, it may be hypothesized that the tracks were created (Figure 3) by small- to medium-sized theropods (ranging in weight from only tens to hundreds of kilograms). Unfortunately, no Middle Jurassic dinosaur remains are currently known the United States.

Over 1000 theropod tracks have been discovered at the Red Gulch Dinosaur Tracksite, making the RGDT the most extensive dinosaur tracksite known in Wyoming. Mapping efforts documented over 630 tracks (representing 40 trackways) from the Ballroom, approximately 280 tracks (representing 49 trackways) from the Discovery Area (Figure 4), and over 200 tracks (representing 36 trackways) from 23 outcrop outliers of the track-bearing Sundance Formation within the 1600 square meters of the RGDT. Arranged into at least 125 discrete trackways (ranging from 2 to 45 steps), these tracks offer a unique glimpse of dinosaurs walking in water-saturated, thixotropic sediments close to the shore of an inland seaway. A statistical analysis of 425 individual footprints, measured from mylar tracings, indicates that no distinct morphologic clustering is apparent, thus indicating that only one taxon of dinosaur is represented at the RGDT (Sizemore, 2000).

FIGURE 3. Hypothetical Middle Jurassic dinosaur trackmaker for the Red Gulch Dinosaur Tracksite. Drawing by Thomas Adams.

Because of the large population and areal extent, important morphological and preservational variations within and between trackways were analyzed. Irregular step lengths, variable straddle widths, and swerving trackway paths may be related to variations in substrate microenvironments or to intracommunity dynamics. The majority of the trackways show preferred orientations with two trends of parallel to subparallel groupings to the south and southwest, suggesting gregarious behavior. However, several solitary trackways trend in opposite and perpendicular directions; dispelling the existence of any confining barriers. Analysis of the various trackways with regard to time sequencing, origin, direction of travel, speed, and changes in morphology are currently in progress. Preliminary analyses indicate that the majority of dinosaurs were "walking" with an average speed of approximately 6 kilometers per hour.

METHODOLOGY

Standard vertebrate ichnological field methods discussed by Thulborn (1990) and Lockley (1991) were incorporated during the study of the Red Gulch Dinosaur Tracksite. The first step in the study of dinosaur tracks was finding and discovering the extent of the track-bearing layer. Mapping and study focused on exposures within the RGDT, but continued prospecting of correlative beds was an ongoing process throughout the course of the investigation and will continue into the future.

The track mapping process began with clearing the surface of covering debris. This entailed removing a thin veneer of unconsolidated material that had obscured the tracks and did not require the removal of thick deposits of overburden or disturbance of large, established vegetation. Because the area is so large, teams of well-supervised volunteers were utilized for the large and small scale sweeping. In addition, the surface was systematically sprayed with water via a portable water tank equipped with a gas-powered pump and a hose, allowing for the surface to be cleaned as necessary.

Each track located was marked (Figure 5) and numbered in chalk on the outcrop and sketched onto a map with a scale of 1 inch = 1 meter. This map was continually updated and redrafted. The one square meter grids for this map were laid out on the outcrop surface utilizing a Topcon standard total station (Figure 6) or a Geodimeter System 4000 one-man total station with a robotic unit and data collector (Figure 7). Grid corners were marked on the limestone surface with a permanent black marker circle no more than 2 cm in diameter. This practice did not permanently mar the track surface, as the grid points resemble the lichen that occur naturally on the surface. The ink weathered away over the course of a year or two. In addition, the locations of toe and heel points were captured using the Geodimeter System 4000 total station. Global Positioning Systems coordinate data were used to bring the surveyed points into a real world coordinate system.

By the end of 2000, approximately 900 grids within the dry wash were mapped, measured and photodocumented. All grids of the Ballroom and Discovery Area containing tracks were photographed with a metric camera. Track density varied throughout the Red Gulch Dinosaur Tracksite, ranging from 0-8 tracks per square meter. In addition, each track was documented. Description and measurements taken on individual tracks included: identification number, location, size,

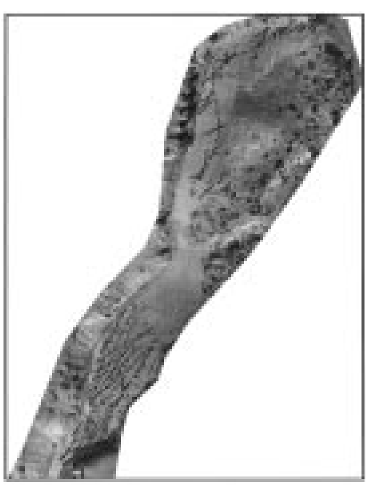


FIGURE 4. Red Gulch Dinosaur Tracksite "dry wash" (photo from Low Altitude Remote Controlled plane) with track points located from total station; "Discovery Area" (north), "Ballroom" (south).

FIGURE 5. Red Gulch Dinosaur Tracksite footprint with toe and heel points marked and numbered.

FIGURE 6. Volunteer Susan Horn (Kentucky teacher) surveying in the "Discovery Area".

shape and arrangements of digits, with special attention to the presence of claw marks, digital pads, and other distinctive track features. The lengths of individual digits were measured, as well as the overall pes length, width and depth (Figure 8). The angles between each digit were noted with the orientation direction of the foot midline, to note direction of rotation of each print. Over 20,000 track attributes were recorded at the RGDT and entered into an Excel spreadsheet.

Trackway segments were also noted. Measurements of adjacent steps, stride lengths, and pace angles were used for gait and speed analysis. Length of trackways and distance between adjacent trackways were also analyzed. Select miscellaneous biogenic (e.g., invertebrate trace fossils) and inorganic features (e.g., salt casts, ripple marks) associated with the tracks were noted, measured and photographed. Mylar tracings were made of significant, individual tracks and trackways. Information on variation in the degree of track preservation throughout the exposure was noted and time-sequencing of tracks (overprinting) analyzed. Throughout the project, variations in surveying, mapping, photographing, and describing the tracks were noted when different individuals were involved. To maintain consistency, one individual was selected to do all track measurements and others were each delegated their own specific tasks. We strongly recommend assignment of select duties to single individuals for consistency in documentation and information dissemination.

It was planned that few tracks would be permanently removed from the Red Gulch Dinosaur Tracksite for study purposes, as this would detract from the overall aesthetic value of the site (Thulborn, 1990; Lockley, 1991). However, those tracks in danger of destruction or theft were noted and some outside of the dry wash were removed for microscopic study. Castings of select tracks and trackways were made for publication photography/drawing, interpretive displays, and as teaching tools. Liquid latex is the least destructive casting medium, but high grade silicone may be used for its superior detail resolution and mold reusability, if the individual track surface is competent enough to withstand the stronger stresses involved. Both compounds were used at the RGDT. As the track-bearing limestone is fractured and highly fissile, hard casting media should not be used. Unfortunately, plaster and resin casts taken at the RGDT by unpermitted individuals irreparably damaged some of the tracks (Milstein, 1998).

To preserve the data of this unique paleontological resource, monitor weathering, and facilitate the scientific research of the tracks, the Red Gulch Dinosaur Tracksite was intensively photodocumented. A variety of photographic methods have been used to document the tracks at the RGDT. Imagery of the tracksite ranges from 30-meter resolution sat-

FIGURE 7. Ty Naus (South Dakota School of Mines and Technology student) surveying "Ballroom" with Geodimeter total station.

FIGURE 8. Beth Southwell mapping tracks at the Red Gulch Dinosaur Tracksite.

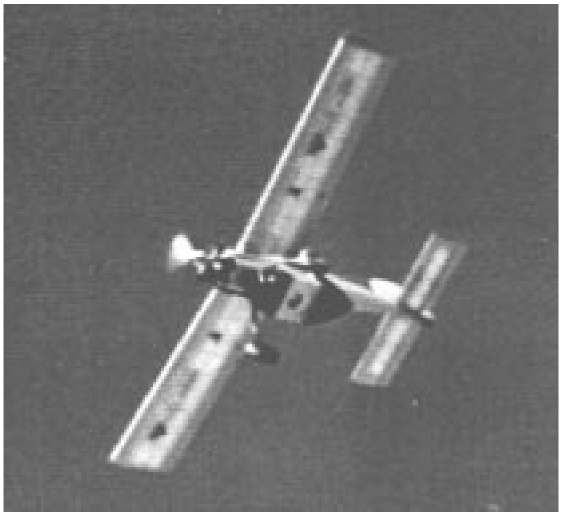


FIGURE 9. Low Altitude Remote Controlled plane with mounted 35mm camera flying over the Red Gulch Dinosaur Tracksite.

ellite data to close-range photogrammetric images of a single track. Large format (9"x9") natural color aerial photography was flown in the fall of 1998 at scales of 1:12,000, 1:3000, and 1:1800 with an endlap of 60% to ensure stereoscopic coverage. The large format aerial photography, while suitable for developing management and recreation plans for the RGDT, did not provide the level of detail needed to illustrate track and trackway relationships. To fill the gap, a 35-mm camera was mounted on a Low Altitude Remote Controlled plane (Figure 9) and used to photograph the main track-bearing surface (i.e., "dry wash"). The resulting photographs were scanned, mosaicked, and registered to the digital orthophoto. These images were georeferenced with the survey data for use in Geographic Information Systems (GIS) technology. In addition, the "Ballroom" was photographed and videoed from an Ultralight aircraft. However, camera motion was a noticeable problem for all pictures taken from planes. Aerial cameras take still pictures while the plane is moving, resulting in blurred images. For most aerial photography this is not a problem, as the resolution of extremely high levels of detail is not necessary. To rectify this problem a tethered blimp with a 50x70 mm. format camera and light-weight video camera was used at the RGDT (Figures 10 and 11).

FIGURE 10. Tethered blimp with mounted camera over the balloon.

Photogrammetry, which involves making precise measurements from photographs, was used as a noninvasive strategy for collecting three-dimensional data above the track surface (Matthews and Breithaupt, 2001). Tracks and grids were photographed from three different tripod heights ranging from roughly 2-10 meters. Close-range photogrammetry at 174 cm above the surface was used to document the track surface on a meter by meter basis, with the camera angle positioned parallel to outcrop dip (Figure 12). To increase the accuracy of the measurements a metric camera is required.

The advantages obtained by using a metric or calibrated camera are that the lens distortions have been measured and that a system of fiducials whose coordinates are known to the nearest micron are imprinted on each frame. A Rollieflex 3003 metric 35-mm surveying camera was used at the Red Gulch Dinosaur Tracksite. To further preserve and record the paleontological resources on the main track-bearing surface, each one-meter grid in the "dry wash," which contained a track, was photographed using the metric camera and a 1.05 meter square grid, which provided internal horizontal and vertical control. These photographs were scanned, rectified, mosaicked, and georeferenced using the total station coordinates.

The close-range photographs, as well as other scientific observations, are being integrated into a real-world, rectangular coordinate system that provide the framework for a Geographic Information System of the Red Gulch Dinosaur Tracksite. The GIS will be used to analyze the relationships of the scientific data in 3-D space, and eventually be used to build 3-D models of select tracks found at the site. Detailed measurements, such as digital terrain models and topographic contours, can be produced for the individual tracks (Figure 13) utilizing a Zeiss P3 Analytical Stereoplotter. These models preserve information about the footprints which may be lost through time as the result of illegal collection, vandalism, erosion, and human interaction and can be used to monitor and manage the site in the future.

Incorporating Geographic Information Systems documentation methodologies with traditional ichnology research methods in the course of the study at the Red Gulch Dinosaur Tracksite, have resulted in one of the most precise approaches for the measuring, recording, and evaluating of fossil tracks. In addition, various track documentation methodologies are being compared as to their utility. State-of-the-art technology utilized at this site, has resulted in the RGDT gradually becoming one of the most extensively documented dinosaur tracksites in the world.

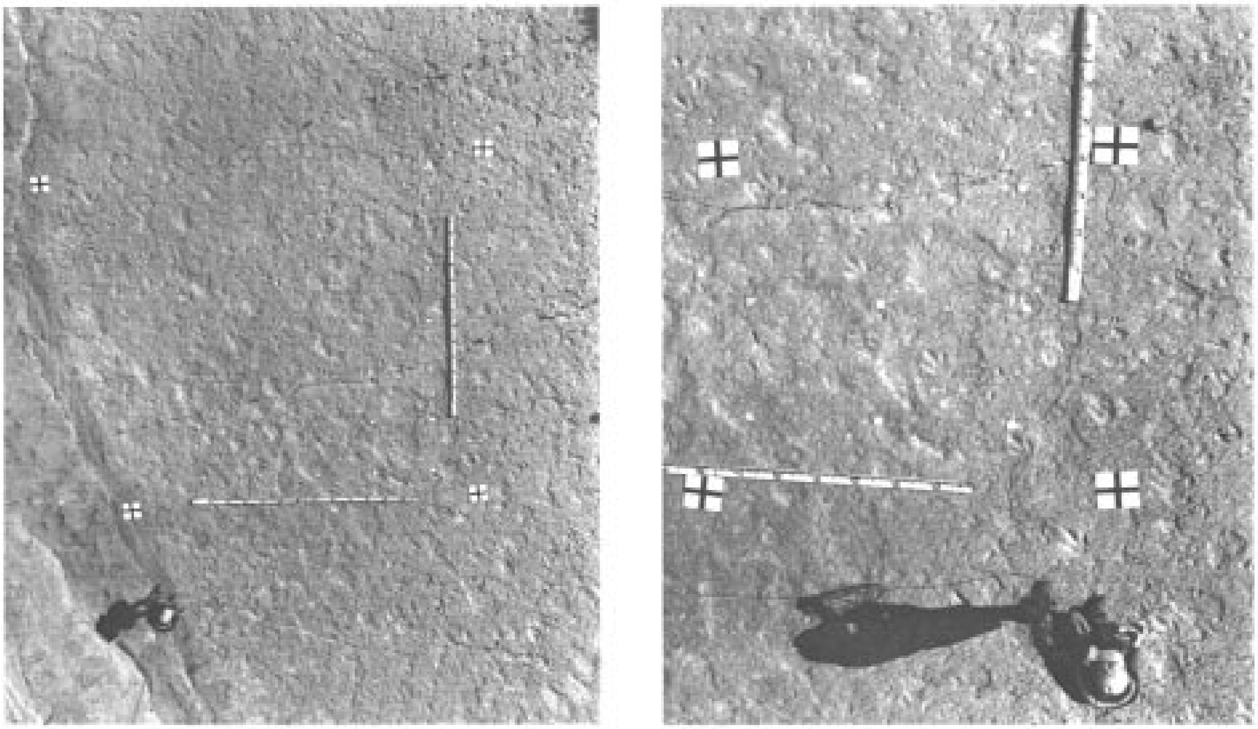


FIGURE 11. Low-level aerial photos of tracks in the "Balloon" from the blimp.

FIGURE 12. Brent Breithaupt and Neffra Matthews photographing a meter grid in the "Balloon".

PUBLIC EDUCATION

Dinosaurs have always excited the public's interest and with the recent spate of dinosaur films, that interest level is higher than ever. The Red Gulch Dinosaur Tracksite has the potential to become a popular, paleontological interpretive site. The RGDT is a unique, North American, dinosaur fossil site located on public land and is readily accessible for educational opportunities and public involvement. To this end, investigators coordinated their work with the BLM to accurately disseminate vertebrate ichnology data from the RGDT. We have worked closely with the BLM to develop plans that have accommodated the needs of the general public and media, without negatively impacting the scientific research. Because of this coordinated effort the public and media could visit the site without the research being impeded. Proximity the site to the existing Red Gulch/Alkali National Back Country Byway allows ready access for the public to view the tracks *in situ*.

In addition, we are assisting the BLM in the development of the site as a unique tool for public education by aiding in the development of interpretive displays, tour materials and guidebooks, K-12 classroom materials, and websites. We have successfully disseminated information about the site to the general public through newspaper and magazine stories, as well as television productions. Additionally, building on suggestions and ideas presented by other science educators (Munsart, 1993; Zike, 1994; Munsart and Van Gundy, 1995), we plan to provide some exciting interactive teaching exercises (Figure 14), which will utilize the track information available at the Red Gulch Dinosaur Tracksite and allow students (Figure 15) to do their own "footprint sleuth-

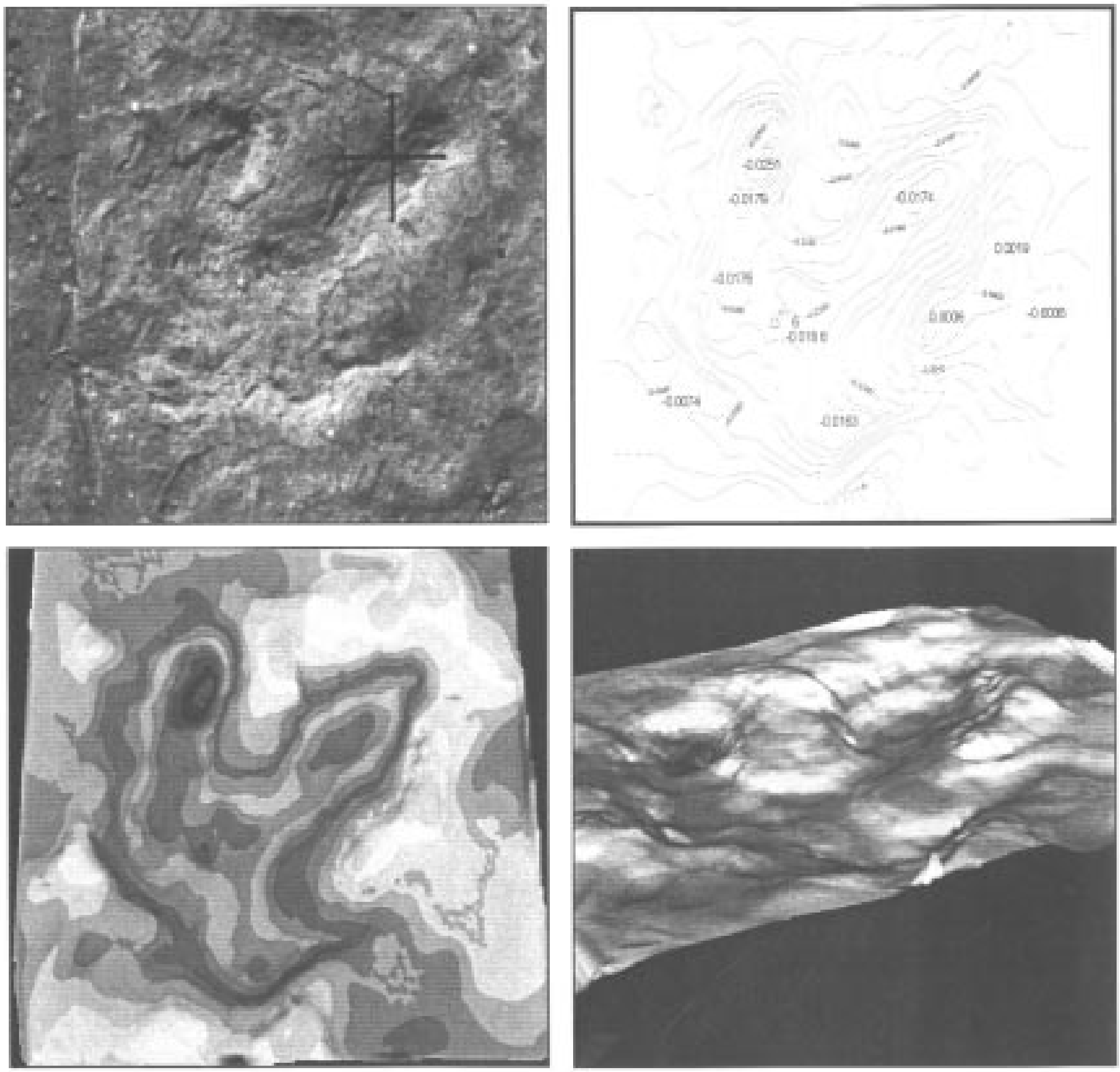


FIGURE 13. Photo of Red Gulch Dinosaur Tracksite footprint (upper left); digital contour of track (upper right); Digital Terrain Model of track, planar view (lower left); and Digital Terrain Model of track, oblique view (lower right).

ing" (Bakker, 1996). The size and complexity of the site presents an opportunity for students of all ages to practice their observational skills, descriptive techniques, critical thinking and mathematical skills. It has been our ongoing interest (Breithaupt, 1992; Leite and Breithaupt, 1993; Breithaupt, 1996) to utilize the unique fascination people have with dinosaurs and their world to teach science in a fun and intellectually stimulating way.

FIGURE 14. School group "walking like a dinosaur" along dinosaur tracks in the "Balloon".

ACKNOWLEDGMENTS

Appreciation is extended to all of the students and volunteers who made this project so enjoyable. Thanks to BLM paleontologist Laurie Bryant for her assistance in the project. Gratitude is extended to various BLM representatives, especially those of the Worland Office, for their help in arranging and participating in this project. Various anonymous reviewers provided valuable suggestions on this manuscript. Finally, thanks goes out to the BLM for assistance in funding this program.

REFERENCES

BAKKER, R.T., 1996. Dr. Bob's guide to teaching dinosaur science: World Book, Inc., Chattanooga, 16 pp.

BREITHAUPT, B.H., 1992. The use of fossils in interpreting past environments: in: Goldman, C.A. (ed.), Tested studies for laboratory teaching: 13th Workshop/Conference, Association for Biology Laboratory Education, Proceedings, v. 13, p. 147-158.

_______, 1994. Wyoming's dinosaur diversity: in Nelson, G.E. (ed.), The dinosaurs of Wyoming: Wyoming Geological Association, 44th annual Field Conference Guidebook, Casper, p. 101-104.

_______, 1996. Fossilization and adaptation: Activities in paleontology: in Scotchmoor, J. and McKinney, F.K. (eds.), Learning from the fossil record, The Paleontology Society Papers, v. 2, p. 157-165.

Clark, J.M., J.M. Montellano, J.A. Hopson, R. Hernandez, and D.E. Fastovsky, 1994. An Early or Middle Jurassic tetrapod assemblage from the La Boca Formation, northeastern Mexico: in Fraser, N.C. and Sues, H.D. (eds.), In the shadow of the dinosaurs, Early Mesozoic tetrapods, Cambridge University Press, Cambridge, U.K., p. 295-302.

Darton, N.H., 1899. Jurassic formations of the Black Hills of South Dakota: Geological Society of America Bulletin, v. 10, p. 383-396.

Dodson, P., 1997. Jurassic Period: in Currie, P.J. and Padian, K. (eds.), Encyclopedia of dinosaurs, Academic Press, San Diego, CA, p. 387-388.

Farlow, J.O., 1987. A guide to Lower Cretaceous dinosaur footprints and tracksites of the Paluxy River Valley, Somervell County: Field Trip Guidebook, 21st Annual Meeting, south-central section, Geological Society of America, Waco, Texas, 50 p.

Fastovsky, D.E., J.M. Clark, N.H. Strater, M. Montellano, R. Hernandez, and J.A. Hopson, 1995. Depositional environments of a Middle Jurassic terrestrial vertebrate assemblage, Huizachal Canyon, Mexico: Journal of Vertebrate Paleontology, v. 15(3), p. 561-575.

Ferrusquia-Villafranca, I., E. Jimenez-Hidalgo, and V.M. Bravo-Cuevas, 1996. Footprints of small sauropods from the Middle Jurassic of Oaxaca, southeastern Mexico: in Morales, M., The continental Jurassic, Museum of Northern Arizona Bulletin 60, p. 119-126.

Foster, J.R., A.H. Hamblin, and M.G. Lockley, 2000. The oldest evidence of a sauropod dinosaur in the western United States and other important vertebrate trackways from Grand Staircase-Escalante National Monument, Utah: Ichnos, v. 73, p. 169-181.

Gillette, D.D., 1996. Stratigraphic position of the sauropod *Dystrophaeus viamalae* Cope 1877 and its evolutionary implications: in Morales, M., The continental Jurassic, Museum of Northern Arizona Bulletin 60, p. 59-68.

Kilibarda, Z. and D.B. Loope, 1997. Jurassic aeolian oolite on a Paleohigh in the Sundance Sea, Bighorn Basin, Wyoming: Sedimentology, v. 44, p.391-404.

Leite, M.B. and B.H. Breithaupt, 1993. Teaching paleontology in the National Parks and Monuments: A curriculum guide for teachers of the second and third grade levels: National Park Service, Department of the Interior, 105 p.

Lockley, M., 1991. Tracking dinosaurs: Cambridge University Press, Cambridge, 238 p.

Figure 15. Student looking for dinosaur footprints at the Red Gulch Dinosaur Tracksite.

______, 1997. Footprints and trackways: in, Currie, P.J. and Padian, K. (eds.), Encyclopedia of dinosaurs, Academic Press, San Diego, CA, p. 242-245.

Lockley, M. and A.P. Hunt, 1995. Dinosaur tracks and other fossil footprints of the western United States: Columbia University Press, 338 p.

Lockley, M., A.P. Hunt, and S.G. Lucas, 1996. Vertebrate track assemblages from the Jurassic Summerville formation and correlative deposits: in Morales, M. (ed.), The continental Jurassic, Museum of Northern Arizona Bulletin 60, p. 249-254.

Lockley, M., A.P. Hunt, M. Paquette, S.A. Bilbey, and A. Hamblin, 1998. Dinosaur tracks from the Carmel Formation, northeastern Utah: implications for Middle Jurassic paleoecology, Ichnos, v. 5, p. 255-267.

Lockley, M. and C. Meyer, 2000. Dinosaur tracks and other fossil footprints of Europe, Columbia University Press, New York, 323 p.

Matthews, N.A. and B.H. Breithaupt, 2001. Close-range photogrammetric experiments at Dinosaur Ridge, Mountain Geologist, v. 38 (3), p. 147-153.

Milstein, M., 1998. Popularity threatens dino traces. Billings Gazette, September 27.

Munsart, C.A., 1993, Investigating science with dinosaurs: Teacher Ideas Press, Englewood, CO, 248 p.

Munsart, C.A. and K.A. Van Gundy, 1995. Primary dinosaur investigations: Teacher Idea Press, Englewood, CO, 292 p.

Peterson, J.A., 1957. Marine Jurassic of Northern Rocky Mountains and Williston Basin: A.A.P.G. Bulletin, v. 41(3), p. 399-440.

Schmude, D.E., 2000. Interplay of paleostructure, sedimentation and preservation of Middle Jurassic Rocks, Bighorn Basin, Wyoming, The Mountain Geologist, v. 37 (4), p. 145-155.

Shubin, N. and H.D. Sues, 1991. Biogeography of early Mesozoic continental tetrapods: patterns and implications: Paleobiology, v. 17, p. 214-230.

SIZEMORE, J.A., 2000. Analysis of tridactyl dinosaur footprints from the Middle Jurassic Sundance Formation of Wyoming, Senior Thesis, Butler University, 59 p.

SOUTHWELL, E.H. AND B.H. BREITHAUPT, 1998. Wyoming's vertebrate tracks: 130 years of discovery: Journal of Vertebrate Paleontology, v. 18 (3), p. 79A.

SOUTHWELL, E.H. AND M.G. LOCKLEY, 1996. First reports of dinosaur tracks from the Morrison Formation, Como Bluff, Wyoming: in Hunter, R.A. (ed.), Paleoenvironments of the Jurassic, Tate Geological Museum Guidebook no. 1, Casper College, Casper, WY, p. 81-87.

THULBORN, T., 1990. Dinosaur tracks: Chapman and Hall, New York, 410 p.

WEISHAMPEL, D.B., 1990. Dinosaur distribution: in Weishampel, D.B., Dodson, P. and Osmolska, H. (eds.), The Dinosauria, University of California Press, Berkeley, p. 63-139.

WHYTE, M.A. AND M. ROMANO, 1994. Probable sauropod footprints from the Middle Jurassic of Yorkshire, England: Gaia: Revista de geociencias, Museau Nacional de Historia Natural, Lisbon, Portugal, 10, p. 15-26.

ZIKE, D., 1994. Dinosaur studies in the pre-K through junior high curriculum: in Rosenberg, G.D. and Wolberg, D.L. (eds.), Dinofest, The Paleontological Society Special Publication no. 7, p. 109-116.

ESTABLISHING BASELINE PALEONTOLOGICAL DATA FOR RESEARCH AND MANAGEMENT NEEDS: LESSONS LEARNED FROM THE NPS ALASKA REGION

ANTHONY R. FIORILLO[1], VINCENT L. SANTUCCI[2], ROLAND A. GANGLOFF[3], PETER J. ARMATO[4], AND RUSSELL KUCINSKI[5]

[1]Dallas Museum of Natural History, P.O. Box 150349, Dallas, TX 75315

[2]Fossil Butte National Monument, P.O. Box 592, Kemmerer, WY 83101

[3]University of Alaska Museum, 907 Yukon Dr., Fairbanks, AK 99775

[4]Kenai Fjords National Park, P.O. Box 1727, Seward, AK 99664

[5]National Park Service - Alaska Support Office, 2525 Gambell St., Anchorage, AK 99503

ABSTRACT—As part of a mandated inventory and monitoring program within the National Park Service, a large-scale study of paleontological resources has been initiated within the parks and monuments of the Alaska Region. This paper will discuss the complexities of working within the Alaska Region, and the preliminary data recorded. Within the Alaska Region, the scope of a paleontological survey is enormous, even for one park. A small team prospected accessible localities within six park units, targeted because the park management could provide either direct funding or in-kind support for the field inventories. The crew size was based on budget and logistics. The attention each park received was based on a combination of geology, weather conditions, personnel and other logistical parameters. Ground inspection revealed many inconsistencies or errors in the published geologic maps for each region. In one particular example, a region mapped as Early Jurassic in age has produced fossil evidence to suggest a Paleogene age for at least part of the region. This is particularly significant in this Park as there are no such rocks of Paleogene age previously identified throughout the western part of the park. Preliminary results from these surveys show great potential for future work. The scale of current mapping is insufficient to address both detailed paleontological questions and current resource management issues. More complete survey data will provide the needed baseline information for paleoecological questions within the Alaska Region, and throughout western North America for similarly aged rock sequences.

INTRODUCTION

As part of a mandated inventory and monitoring program within the National Park Service (NPS), a large-scale study of paleontological resources has been initiated within the parks of the Alaska Region. A preliminary survey of paleontological resources within NPS areas in Alaska was conducted in 1995 (Santucci, et al., 1995). The purpose of this report is to discuss the complexities of working within the Alaska Region, an enormous geographic area that contains many park units encompassing tens of millions of acres of land. In addition to the paleontological research challenges, these parks provide numerous logistical challenges that include extensive roadless areas, wildlife interactions, and extreme weather conditions. Of these many park units, we initiated paleontological investigations in six units, Aniakchak National Monument and Preserve (ANIA), Denali National Park and Preserve (DENA), Katmai National Park and Preserve (KATM), Kenai Fjords National Park and Preserve (KEFJ), Lake Clark National Park and Preserve (LACL), and Yukon-Charley Rivers National Preserve (YUCH). Partly as a function of funding, and partly as a function of scheduling, we have focused field activities in two park units, Aniakchak and Katmai. Therefore, we will discuss the preliminary data recorded from these parks that highlight the scale of paleontological issues, with respect to research and management needs, that face parks within this region.

These preliminary results show the potential wealth of paleontological information still to be gathered in each of these six parks. Further, as discussed elsewhere (Fiorillo et al., 1996) these discoveries illustrate the point that important management issues may include resources not traditionally recognized within individual parks.

WHY FOSSILS ARE IMPORTANT

It has been suggested elsewhere (Fiorillo, 2000) that perhaps no other subdiscipline of the earth sciences can make the singular claim of having the attention and enthusiasm of the general public, as can paleontology. Public fascination with fossils is historical, at least dating back to the earliest public displays of dinosaurs in the mid- and late 19th century. That this fascination with paleontology continues today is clear from the vast number of stories in the news regarding fossils. Similarly, college-level dinosaur courses are one of the two most popular earth science courses offered according to one survey, the other course being an offering on the geology of the national parks (Lessem 1994).

Federal land and resource managers concerned with the valuable paleontological resources under their care ask who should be allowed access to these resources? This question stems, in part, from increased public use of federal lands. It also is derived from the increasing tendency by some non-scientists to view fossils as commercial commodities, as evident in the recent announcements of scientifically significant fossils that have been sold at substantial prices (Reed and Wright, 2000).

Increased attention to fossils by federal land and resource managers is not only timely – it is imperative given the following: the broad range of public interest in fossils, the passionate advocacy of opposed special interest groups, the appeal that such controversy has among the media, and the economic and legal impacts of an expanded array of special uses of fossil resources across the federal estate. Given the economic and legislative issues at stake, a greater awareness of fossil resources on public lands is now mandatory.

METHODS

A team of resource managers and researchers was assembled to compile baseline paleontological resource data in the National Park Service units in the Alaska Region using the following criteria. First, resource managers needed to have a basic appreciation and understanding of paleontological issues. A team of such managers was identified and assembled. Second, NPS Alaska Region managers needed to establish partnerships with paleontologists familiar with the local fossils and the associated management issues. Though these initial surveys are research driven, development of products helpful to resource managers was also a significant component of the project. Paleontological researcher partners were identified based on previous paleontological projects within the National Park Service, or within similar federally managed, publicly owned lands.

Through successive meetings between primary parties, scientific objectives were outlined, funding strategies were developed and management needs were highlighted. After obtaining initial funding, responsibilities were divided along areas of training. Researchers pursued research objectives while managers assisted in logistical operations and developed criteria for products to assist park management staff.

In addition to the research benefits of this project, partnering with museum-based paleontologists provides the National Park Service with additional benefits that include access to additional experienced interpretive and exhibits staff, potential development of public education programs and exhibit programs that serve to increase public awareness of NPS park units. This increased public awareness by museum partnerships is particularly helpful to Alaska parks where visitation, compared to similar parks in the lower 48 states, is minimal.

The basic field design used in this study incorporated standard paleontological mapping and collecting methods. Extensive field notes and photographs were taken during the surveys and hand specimens were collected at key locations. Key sites were recorded using a hand-held GPS unit. Moving from one geographic area to another within a park required the use either of trucks, planes or boats, or a combination of these three. Use of these vehicles was often coordinated with other activities by park staff.

In some areas, such as within parts of Katmai National Park, survey activity was coordinated with the seasonal activities of the brown bear population to reduce the probability of bear-human conflicts. Also, given the remoteness of other areas, and thereby the high cost of accessing these areas, some aspects of work were intimately coordinated with ongoing biological surveys (i.e. salmon runs). Once an area was accessed, detailed surveys were performed on foot.

ANIAKCHAK NATIONAL MONUMENT AND PRESERVE

Aniakchak National Monument and Preserve consists of approximately 600,000 acres, and is one of the least visited parks within the National Park Service (Fig. 1). The park was established in 1978 to preserve the the immense volcanic features in the region. The most notable of these features is the 6-mile wide Aniakchak Caldera, a 2,000 foot deep circular feature produced by the collapse of its subsurface magma chamber after an eruption about 3,400 years ago (Miller, 1990). The recognized resources of the park include this volcanic feature and elements of the modern flora and fauna.

The area discussed here is along the Gulf of Alaska coastline in Aniakchak Bay, which currently has geologic map coverage (Detterman et al., 1981; Wilson et al. 1999). However, based on these previous published reports, differentiation between the geology of the two areas discussed below is ambiguous. Our paleontological observations clarify the

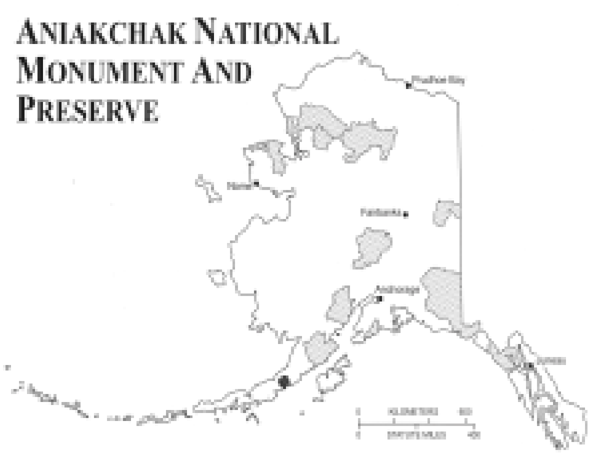


FIGURE 1. Map of Alaska showing the location of Aniakchak National Monument and Preserve.

geologic differences in the mapped Mesozoic geology along this part of the coast of Aniakchak National Monument and Preserve. Further detailed work in this park will likely clarify similar discrepancies.

The following comments are based on literature surveys and field observations. Field observations were made during a low elevation flight over the monument. The path of the flight was from King Salmon to the west side of Aniakchak Crater, past the Gates, and down the Aniakchak River to Aniakchak Bay (Fig. 2). At the bay, the flight proceeded north to the southern half of Amber Bay. A stretch of beach was chosen for a landing on the southern side of Cape Ayutka in what is mapped as Pleistocene material. Examination of outcrops occurred on the south side of Cape Ayutka proper on an unnamed point of land southwest of Cape Ayutka.

THE NAKNEK FORMATION

The investigation focused on the Mesozoic strata in Aniakchak National Monument and Preserve. More specifically, as vertebrate fossils have the highest proven financial value in commercial trade, the survey is focused on Late Jurassic through Cretaceous rocks approximately 150 – 65 million years ago. Included in this sequence is at least one rock unit, the Upper Jurassic Naknek Formation, that has great potential for producing skeletal material or footprints of dinosaurs.

In the Black Lake area of the western Alaska Peninsula a slab of rock has been photographed showing several tracks of a three-toed, predatory dinosaur, but its precise location is unknown (Gangloff, 1998). Given the approximate location of this slab, and unpublished geologic survey work on the Alaska Peninsula (Wilson, pers. comm., 2000), this slab is most likely in the Naknek Formation. The Naknek Formation extends through Aniakchak, Katmai and Lake Clark. Access to rock exposures is varied.

The Naknek Formation is the most widespread Mesozoic rock unit on the Alaska Peninsula, extending from the base of the peninsula southwestward to Black Hill. Spurr (1900) named the formation during the first comprehensive geological survey of the region. Though the exact application of the term has undergone some alteration in subsequent years (summarized in Detterman et al., 1996), most important to this report has been the subdivision of the Naknek Formation into members. From oldest to youngest, the Chisik Conglomerate, Northeast Creek Sandstone, Snug Harbor Siltstone, Indecision Creek Sandstone, and Katolinat Conglomerate Members (Detterman et al., 1981; Detterman et al., 1996). In general, these members represent a depositional change from a dominantly terrestrial fluvial system to a moderately deep to shallow marine environment. The maximum stratigraphic thickness of the Naknek Formation through the Alaska Peninsula is approximately 3200 meters, though the average thickness is between 1700 – 2000 meters (Detterman et al., 1996).

Based on marine invertebrate fossils, the age of the Naknek is generally considered as Oxfordian to Tithonian (Detterman et al., 1996). The approximate date for the basal boundary of the Oxfordian is 157 million years and that for the upper boundary of the Tithonian is 146 million years (e.g., Harland et al., 1989). These dates define the interval as the Late Jurassic.

THE CHIGNIK FORMATION

The Chignik Formation was named by Atwood (1911) for rocks exposed in the vicinity of Chignik Bay, southwest of Aniakchak National Monument. This Upper Cretaceous rock unit has a maximum stratigraphic thickness of approximately 600 meters in the type area of Chignik Bay, southwest of the boundary of Aniakchak National Monument and Preserve (Detterman et al., 1996). In the area of Chignik Bay, the Chignik Formation exhibits a cyclic pattern of nearshore marine, tidal flat, nonmarine channel and floodplain depositional environments. These are all potentially fossil vertebrate-bearing environments of deposition. However, the Chignik Formation rapidly changes character becoming exclusively marine to the northeast and southwest of Chignik Bay. The relationship of this change to the boundaries of Aniakchak National Monument and Preserve is unclear.

The age of this rock unit is late Campanian to early Maastrichtian (Late Cretaceous), based on marine invertebrate fossils. The Campanian-Maastrichtian boundary is

FIGURE 2. Cessna carrying paleontology field team lands on the beach along the coastline of Aniakchak Bay.

generally considered to be 74 million years ago (e.g. Harland et al., 1989).

CAPE AYUTKA

The rocks exposed at Cape Ayutka are identified as the Naknek Formation and are amply exposed as a continuous cliff. The rocks are fine-grained, dark gray siltstones. Buff colored concretions are common. Gastropods (snails) and pelecypods (clams) are common and diverse in type. In places along these cliffs pelecypods occur locally as dense shell beds. All snails occurred as isolated shells. Carbonized plants were rare. A typical large tree limb measures almost 20 cm wide and 100 cm long. One such limb of these proportions showed evidence of burrowing by an additional, unidentified fossil invertebrate.

UNNAMED POINT SOUTHWEST OF CAPE AYUTKA

These rocks are exposed as a nearly continuous set of cliffs. Contained in this set of cliffs is an igneous dike of unknown age. The sedimentary rocks in these cliffs are the Chignik Formation and consist of coarse sands with some conglomeratic layers. These conglomerates are up to 30 cm thick and contain pebbles up to 6 cm in diameter, though most are 4 cm or less. The pebbles are primarily crystalline material but a rare number of clasts appear to be made of coal. Plant debris is very common and includes fossil tree limbs up to 1m in length and pulverized plant debris forming mats along bedding surfaces. Towards the southwest end of these cliffs the sedimentary rocks become finer grained. No fossils were observed in this fine-grained sequence of rocks.

ANIAKCHAK CONCLUSIONS

Current geologic map coverage is ambigious along the coast of Aniakchak National Monument and Preserve. This ambiguity is due to: a) the fact that very similar colors are used on the geologic map in both areas discussed here (Detterman et al., 1981); b) the areal extent of each area on the map is limited and therefore presumably precluded clarification by standard map designations, and; c) the scale of the current map coverage is exceptionally large. This report shows that two distinctly different Mesozoic formations are present in the area and these rock units have very different fossil occurrences. Further detailed work will likely clarify similar discrepancies elsewhere in the Monument.

KATMAI NATIONAL PARK AND PRESERVE

Katmai National Park and Preserve is approximately 4,000,000 acres, and is one of the oldest National Park Service units in Alaska (Fig. 3). The national monument was established in 1918, and later expanded and granted park status in 1980. The proclamation of this unit as a national monument was based on the enormous 1912 eruption of Novarupta that produced ashfall for three days and covered 3,000 square miles with pyroclastic debris. Ash was deposited as thick as 200 meters in an area over 65 square kilometers that has since been named the Valley of Ten Thousand Smokes. The recognized resources of the park include this volcanic feature and elements of the modern flora and fauna.

Field checks of geologic maps at various points within the Park showed that, while useful in a very general sense, mapped specifics of park geology are in error. In the vicinity of Ukak Falls, significant discrepancies were evident between the mapped and actual contacts of rock units. This area is currently mapped as Quaternary with Jurassic rocks exposed nearby. However, numerous pelecypods (*Buchia*) and a belemnite were observed *in situ*, indicating Jurassic rocks at the Falls.

Of more profound significance however is the discovery of an unnamed rock unit along the shores of Naknek Lake in the vicinity of Dumpling Mountain (Figure 3), an area that currently has geologic map coverage. Given the magnitude of reinterpretation in this area, this discovery is discussed in some detail below.

DUMPLING MOUNTAIN - CURRENT GEOLOGIC MAP COVERAGE

Current geologic map coverage shows the prominent mountain next to Brooks Camp, named Dumpling Mountain, comprised entirely of the Early Jurassic Talkeetna Formation (Riehle et al., 1993). The Early Jurassic is generally considered to range from approximately 208 million years ago to

TABLE 1. Partial list of fossil plants from a new plant locality in Katmai National Park and Preserve.

Family	Genus	Modern Relative	Geologic Significance
Ulmaceae	*Ulmus*	Elm	
Juglandaceae	*Carya*	Hickory, Pecan	
Betulaceae	*Carpinus*	Birch	
Cercidiphyllaceae	cf. *Cercidiphyllum*	Katsura	
unknown	*Litseaphyllum*	Laurels, Cinnamon tree	Paleogene

FIGURE 3. Map of Alaska showing the location of Katmai National Park.

approximately 178 million years ago (Harland et al., 1989). Dinosaurs evolved approximately 225 million years ago and by the Early Jurassic they had started to become the dominant vertebrate life on earth. Flowering plants, or angiosperms, had not yet evolved. Given the accessibility of Dumpling Mountain from Brooks Camp, a paleontological survey of the mountain was initiated.

SUMMARY OF OBSERVATIONS

A protection ranger at Katmai National Park showed the survey crew a fossil plant locality that she had discovered a few weeks earlier. This site is located along the shore of Naknek Lake, northeast of Brooks Camp and consists of a medium to dark gray, massive siltstone. All of the plant material observed consisted of angiosperm leaves (Fig. 4). Table 1 is a partial list of floral remains recovered.

SIGNIFICANCE

This new fossil locality is unequivocally not in the Talkeetna Formation. This site is part of a rock unit that represents a previously unrecognized interval of geologic history for the entire western drainage of Katmai National Park and Preserve. As such, this site represents a previously unrecognized paleontological resource for the park.

FIGURE 4. Fossil leaf discovered near Dumpling Mountain, Katmai National Park.

The presence of these angiosperms clearly demonstrates a substantial revision in geologic age for part of the area around Dumpling Mountain. Angiosperms become the dominant flora by the middle of the Cretaceous, approximately 90 million years ago, but the age indicated by these floral remains is even younger. Based on the small sample of leaves observed at this site, this site is probably Paleogene in age, an interval of time that extends from 65 to 23 million years ago (Harland et al., 1989). Given the small sample size thus obtained however, a Neogene age cannot be definitively ruled out. Although negative evidence cannot be regarded as totally reliable, the absence of conifers supports the older age because conifers became common by the beginning of the Neogene.

WHAT IS THE ROCK UNIT CONTAINING THESE FOSSILS?

The floral remains suggest that this the site is Paleocene or lower Eocene in age, an interval of time from 66 to 50 million years ago (Harland et al., 1989). However, no such appropriate rock unit has been recognized in the region around Naknek Lake. There are several possible rock unit assignments for this fossil locality.

CHICKALOON FORMATION

The Chickaloon Formation is primarily recognized in the Matanuska Valley and the rock unit has been extended into the upper Cook Inlet region (Wolfe et al., 1966). The rock unit is a sequence of nonmarine sandstones, siltstones, coals, and conglomerates. The flora suggests a subtropical or at least a frost-free floral assemblage. Though it is rich in plant remains indicating a Paleocene age, the accepted extent for this rock unit is well northeast of the fossil locality in Katmai National Park and Preserve.

WEST FORELAND FORMATION

The West Foreland Formation has been mapped as far south as the Cape Douglas area of the Alaska Peninsula (Magoon et al., 1976). A more recent analysis of the rocks of the Alaska Peninsula has shown that the rocks in the Cape Douglas area are much different than those of the type area of the West Foreland Formation. Therefore, those rocks in the Cape Douglas area have been reassigned to the Copper Lake Formation (Detterman et al., 1996).

COPPER LAKE FORMATION

The Copper Lake Formation is a sequence of coarse to fine grained sedimentary rocks that are exposed along the Alaska Peninsula (Detterman et al., 1996). Current geologic mapping of Katmai National Park and Preserve shows these rocks on the Gulf of Alaska side of the park. This rock unit is the right age and is in the closest proximity to the new fossil locality. Given the current data for this fossil site, this locality may be an inland extension of the Copper Lake Formation.

KATMAI CONCLUSIONS

The recognized resources of Katmai National Park and Preserve include volcanic features and elements of the modern flora and fauna. A new fossil locality along the shores of Naknek Lake, near Dumpling Mountain, contains fossils that are inconsistent with the current mapped geology of the area. Based on the fossil recovered in the initial stage of a paleontological survey of Katmai National Park and Preserve, this locality is unequivocally not in the Talkeetna Formation.

This site is part of rock unit that represents a previously unrecognized interval of geologic history for the entire western drainage of Katmai National Park and Preserve. Given the current data for this fossil site, this locality may be an inland extension of the Copper Lake Formation.

Finally, this fossil site represents a previously unrecognized, important new resource for the park. Details of further work will provide Katmai National Park and Preserve with baseline data for management on this previously unrecognized resource. Further, these data can be incorporated in the General Management Plan for the Park, as well as help meet the servicewide goals of the National Park Service Strategic Plan for accountability of paleontological resources.

In addition to the scientific value of the site, given the proximity of this site to Brooks Camp, a major tourist destination for the Park, this site offers untapped interpretation opportunities for the Park, as well as presenting issues for law enforcement rangers.

DISCUSSION

The details presented here are decidedly preliminary and the paleontological points are not to be viewed as scientifically robust. Rather, we use these points to illustrate the fact that in an area as expansive as the Alaska Region, basic data are still in need of being gathered.

In the first example, Aniakchak National Monument and Preserve, the current geologic map coverage is ambiguous for the two mapped polygons in the coastal part of the Park. To a resource manager this ambiguity is significant given that one map polygon is comprised of rocks that have produced fossil vertebrates elsewhere while another map polygon does not. In a park with limited law enforcement resources, clarification of such ambiguities throughout the Park will allow park staff to focus attention where it is needed the most.

In Katmai National Park and Preserve, the current geologic map coverage is perhaps more problematic. Though in large-scale terms the maps are generally reliable, field inspection of mapped contacts between rock units shows inaccuracies. These inaccuracies are a small-scale problem for both researchers and land managers compared to discoveries of the nature of the new plant locality in the vicinity of Dumpling Mountain. In its current state, this new fossil locality is a new resource for Katmai National Park. After more detailed scientific investigation, this site will likely prove to be an important contribution to the understanding of the geologic history of the Park.

In summary, it is not our intention here to be critical of those who worked in the region before us. Rather, survey work in an area without a well-developed logistical infrastructure, like the Alaska Region, lends itself to questions regarding basic baseline data. Well coordinated teams of researchers and land managers can only serve to improve such databases, and these databases in turn can better serve the growing demands that are being placed on public lands.

ACKNOWLEDGMENTS

The authors thank John Bundy, Troy Hamon, Amanda Austin, Mark Wagner, Pavia Wald, and Julie Dreher of the National Park Service in Katmai National Park and Aniakchak National Monument for logistical assistance. Additionally, we appreciate the support provided by Betty Knight, Regional Curator in Alaska. We also thank Bob Higgins and Greg McDonald of the Geological Resources Division of the National Park Service for additional logistical support. We also thank Rick Wilson of the United States Geological Survey for his discussions regarding Mesozoic stratigraphy of the Alaska Peninsula. A. Fiorillo gratefully acknowledges the work of Bonnie Jacobs of Southern Methodist University in providing the floral list in Table 1, but the authors assume full responsibility for additional interpretation presented here. American Airlines, The Jurassic Foundation, and the Dallas Museum of Natural History all provided support for parts of this project.

REFERENCES

Atwood, W.W., 1911. Geology and mineral resources of parts of the Alaska Peninsula. United States Geological Survey Bulletin 467, 137p.

Detterman, R.L., J.E. Case, J.W. Miller, F.H. Wilson, and M.E. Yount, 1996. Stratigraphic framework of the Alaska Peninsula. United States Geological Survey Bulletin 1969-A, p. 1-74.

Detterman, R.L., T.P. Miller, M.E. Yount, and F.H. Wilson, 1981. Geologic map of the Chignik and Sutwik Island Quadrangles, Alaska. United States Geological Survey Miscellaneous Investigations Series, Map I-1229, 1:250,000.

Fiorillo, A.R., 2000. The ancient environment of the Beartooth Butte Formation (Devonian) in Wyoming and Montana: combining paleontological inquiry with federal management needs. *in* Cole, David N. and McCool, Stephen F. eds. Proceedings: Wilderness Science in a Time of Change. Proc. RMRS-P-000. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. v. 3, p. 160-167.

Fiorillo, A.R., R. Harris, and C.L. May, 1996. Late Jurassic (Morrison Formation) dinosaur remains from Curecanti National Recreation Area, Colorado. Park Science. 16(4):14-15.

Gangloff, R.A., 1998. Arctic dinosaurs with emphasis on the Cretaceous record of Alaska and the Eurasian-North American connection; pp. 211-220 *in* S. G. Lucas, J. I. Kirkland, and J. W. Estep (eds.), Lower and Middle Cretaceous Terrestrial Ecosystems. New Mexico Museum of Natural History and Science Bulletin No. 14.

Harland, W.B. and others, 1989. A geologic time scale. Cambridge University Press, Cambridge, 263 p.

Lessem, D., 1994. How to fight dinosaur abuse. *in* Rosenberg, G.D.: Wolberg, D.L. eds., Dino Fest, The Paleontological Society Special Publication 7: 117-125.

Magoon, L.B., W.L. Adkison, and R.M. Egbert, 1976. Map showing geology, wildcat wells, Tertiary plant localities, K-Ar age dates, and petroleum operations, Cook Inlet area, Alaska. United States Geological Survey Miscellaneous Investigations Series, Map I-1019, 1:250,000.

Miller, T., 1990. Aniakchak. *in* Wood, C.A. and J. Kienle (eds.), Volcanoes of North America. Cambridge University Press, p. 58-60.

Reed, C., and L. Wright, 2000. The trouble with fossil thieves. Geotimes, 45(10):22-25,33.

Riehle, J.R, R.L. Detterman, M.E. Yount, and J.W. Miller, 1993. Geologic map of the Mount Katmai Quadrangle and adjacent parts of the Naknek and Afognak Quadrangles, Alaska. United States Geological Survey Miscellaneous Investigations Series, Map I-2204, 1:250,000.

Santucci, V.L., W.P. Wall, and A.M. Mead, 1995. A preliminary survey of paleontological resources from the Alaska Region national parks. *in* Santucci, V.L. and L. McClelland, (eds.), National Park Service Paleontological Research, Technical Report NPS/NRPO/NRTR-96/16, p.8-10.

Spurr, J.E., 1900. A reconnaissance in southwestern Alaska in 1898. United States Geological Survey 20th Annual Report, pt. 7, p. 31-264.

Wilson, F.H., R.L. Detterman, and G.D. DuBois, 1999. Digital data for geologic framework of the Alaska Peninsula, southwest Alaska, and the Alaska Peninsula terrane: U.S. Geological Survey Open-File Report OFR 99-317.

Wolfe, J.A., D.M. Hopkins, and E.B. Leopold, 1966. Tertiary stratigraphy and paleobotany of the Cook Inlet region, Alaska. United States Geological Survey Professional Paper 398-A.

FOSSIL SITES AS NATIONAL NATURAL LANDMARKS: RECOGNITION AS AN APPROACH TO PROTECTION OF AN IMPORTANT RESOURCE

STEVE GIBBONS[1] AND H. GREGORY McDONALD [2]
[1]National Park Service, 909 First Ave., Seattle, WA 98104-1060
[2]Geologic Resources Division, National Park Service, P.O. Box 25287, Denver, CO 80225

ABSTRACT—Over the last thirty-eight years, the National Natural Landmarks (NNL) Program has proven to be a model conservation tool in the recognition, protection, and overall stewardship of ecological, geological, and paleontological resources throughout the United States and its territories. Established in 1962, the National Natural Landmarks Program is administered by the National Park Service in cooperation with other federal, state, municipal, and private landowners. The National Park Service does not typically own lands containing National Natural Landmark resources. However, of the 587 existing National Natural Landmark sites, eighteen NNL's fall within a unit of the National Park Service. Overall, approximately 52% of NNL's are administered by public agencies, more than 30% are privately owned, and the remaining 18% are owned or administered by a mixture of public agencies and private owners.

INTRODUCTION

Protection of fossil resources can take many forms. Many significant fossil sites are located on federal lands and are managed by various agencies such as the National Park Service, Bureau of Land Management and Forest Service, others are on state lands and others on private land. Management of these non-renewable resources depends on their geology, geography and access to the sites, and density and spatial distribution of the fossils. However, the first step in protection and management is always the recognition of their presence and an evaluation of their scientific and educational significance. The discovery of significant fossil sites may be the result of an organized scientific study or paleontological inventory of an area. In some cases it is due to the serendipitous discovery by an interested amateur or a member of the general public who reports the discovery to a paleontologist or a land manager. Scientific study then provides the details of the site significance such as presence of rare species or communities, unusual preservation, unusually complete specimens, preservation of a fauna or flora from a relatively unknown period of geological time, or other special criteria. While the scientific documentation of a site may establish its significance within the paleontological research community, this does not always translate into its recognition by the general public, land managers or landowners. The National Natural Landmarks Program can make the significance of a fossil site known to a broader audience and aid in its long-term protection.

As defined, a National Natural Landmark (NNL) is a nationally significant natural area that has been designated by the Secretary of the Department of the Interior. To be nationally significant, a site must be one of the best examples of a type of biotic community or geologic feature in its natural region. Examples of this natural diversity include terrestrial and aquatic ecosystems, features, exposures, and landforms that record active geologic processes as well as fossil evidence of biological evolution.

There are four major goals or guiding precepts for the National Natural Landmarks Program. These include: **1)** to encourage the preservation of sites illustrating the geological and ecological character of the United States; **2)** to enhance the scientific and educational value of sites thus preserved; **3)** to strengthen public appreciation of natural history; **4)** to foster a greater concern for the conservation of the nation's natural heritage. Besides fostering the basic program goals of natural heritage protection and advancing science and education, some NNL's are the best remaining examples of a type of feature in the country, and in some instances, in the world.

The determination that a site is one of the best examples of a particular feature in a natural region is typically decided using criteria of illustrativeness and condition of the specific feature. Also, in situations that require it, the secondary criteria of rarity, diversity, and values for science and education can be applied.

There are currently fifty-three landmark sites that are paleontological in nature, highlighting the fossil record of 25 states, including the Virgin Islands (Table 1). Besides sites that were designated specifically because of special attributes of their fossil resources; there are other sites that have been designated as NNL's, which may also include fossils. As can be seen in Table 1, NNL's with fossils cover the full range of geological time and all types of fossils, vertebrate, invertebrate, paleobotanical and trace.

Once designated, the National Park Service does not place land use restrictions on these sites. The National Natural Landmarks program simply recognizes and encourages the voluntary, long-term commitment of public and private owners to protect an area's outstanding paleontological values.

TYPES OF MANAGEMENT OF NNL's

Many NNL's with fossil resources are not accessible. In other cases access and interpretation has been enhanced in both the public and private sector. Federal, State and County governments have developed visitor centers at some NNL's to enhance the educational use of the site and thus help the public to understand its context and significance within earth history. The city of Los Angeles maintains both a park and a museum at Rancho La Brea, the internationally famous tar pits located in the heart of Los Angeles. The museum also supports ongoing paleontological research at Rancho La Brea. The state of Connecticut has developed a visitor center at Dinosaur State Park where Triassic dinosaur tracks are preserved, as has Texas at Dinosaur Valley, a Cretaceous Dinosaur Track Site. At Berlin-Ichthyosaur State Park, Nevada, a building has been constructed over the fossiliferous layer to provide long-term protection and serve as an interpretive center. Falls of the Ohio State Park, Indiana provides educational programs and interpretation of an important example of Silurian and Devonian coral reefs. Ginkgo Petrified Forest in Washington is a state park that preserves and interprets petrified logs from the Miocene.

Primarily excavated by paleontologists from the University of Utah, the Cleveland-Lloyd Dinosaur Quarry is administered by the Bureau of Land Management. Buildings over the quarry and a visitor center provide protection of the resources and site interpretation for visitors. Hagerman Fossil Beds National Monument in Idaho was first designated as an NNL and only later became a National Park Service unit. Its recognition as an NNL was an important component of efforts to later establish the area as a national monument. Consequently, it is the only one of the 8 NPS-managed national monuments established because of its fossils and the only one that also has an NNL designation.

Dinosaur Ridge is part of the Jefferson County, Colorado green spaces program. While the property is county owned a non-profit Friends group has been actively involved with the site's ongoing development and provides education programs. As a result of a four-way cooperative program – the Friends of Dinosaur Ridge, paleontologists from the University of Colorado, and Denver and Jefferson Counties - a visitor center has been constructed, interpretive signs installed, and year round educational programs highlighting ongoing scientific research are provided. All labor is on a volunteer basis. Dinosaur Ridge provides an example of one approach towards management of an NNL in which involvement of the federal government has been limited to the NNL site designation.

While many fossil sites with NNL designation on private land are not developed, some have been developed commercially and for educational purposes. The Mammoth Site of Hot Springs, South Dakota is run as a non-profit educational organization. Development of this site has resulted in it becoming a major contributor in encouraging tourism in the town of Hot Springs. This has in turn generated strong community support for the long-term preservation of this important Pleistocene locality. Mississippi Petrified Forest in contrast is a privately owned NNL that has been developed as a for-profit commercial operation. The designation of the site as an NNL figures prominently in their advertising and illustrates the value such a designation can have to encourage the protection of fossil resources on private land. A similar use of the NNL designation is seen in the website for Petrified Sea Gardens (see website address in Table 2).

The previous discussion provides a general overview of the variety of NNL's with fossils and the many different approaches for their long-term management, ranging from no access to high levels of development. How prominent a role the fossils play in these different sites also varies considerably. Many of the sites have web pages; a few examples have been provided in Table 2 for a more complete overview of various management approaches.

THREATENED AND DAMAGED NNL's

Even when fossil sites are recognized as the best remaining examples of a certain period or type locality and have been designated as an NNL, many may still be threatened by a variety of development activities. Building and highway development, oil and gas exploration, and mining are a few examples. The impact to the site may be either direct or indirect.

Although Hagerman Fossil Beds started out as an NNL and is now protected as a national monument they are subject to an indirect threat. Outside of the monument boundaries, farming activities requiring extensive irrigation have produced an artificial perched aquifer. The addition of this water to the loose unconsolidated sediments of the Glenns Ferry Formation has resulted in an increase in the frequency, and in some cases the magnitude, of landslides within the monument. While mitigation of this impact is still underway through cooperative efforts of the monument and the local community, the existence of the threat to the monument illustrates a site's vulnerability even if the source of the threat is indirect.

Sharks Tooth Hill near Bakersfield, California is an NNL designated for its rich deposit of Miocene marine mammals, including whales and sea lions. The site is currently threatened by a proposed housing development adjacent to the site. Since the fossiliferous Temblor formation extends beyond the boundary of the NNL, it is likely that grading and earth movement related to the housing project will uncover scientifically important fossils. The recognition of Sharks Tooth Hill as an NNL and its scientific importance has played a key role in concerns expressed by citizens about the decision by the Kern County Planning Department not to require a paleontologist to be present during the grading. While the

TABLE 1. National Natural Landmarks with Fossil Resources.

State	Name of NNL	Age	Type of Fossils	Ownership
Alabama	Red Mountain Expressway Cut	Silurian	Trilobite	State
Alaska	Middleton Island	Plio-Pleistocene		Federal and Private
	Unga Island, Shumgin Island Group	Tertiary		State and Private
Arizona	Comb Ridge	Triassic	Fossil reptiles	Navajo Indian Nation
	Willcox Playa	Pleistocene	Pollen	Bureau of Land Management
California	Mt. Diablo State Park	Jurassic - Cret Tertiary	vertebrates	State
	Sharktooth Hill	Miocene	Marine vertebrates	Private
	Rancho La Brea	Pleistocene	vertebrates	Municipal
	Rainbow Basin	Miocene	Vertebrates, insects	Bureau of Land Management
	Anza-Borrego State Park	Plio-Pleistocene	vertebrates	State
Colorado	Garden Park Fossil Area	Jurassic	dinosaurs	Bureau of Land Management
	Indian Springs Trace Fossil Sites	Ordovician	Marine trace fossils	Private
	Dinosaur Ridge	Jurassic - Cret	Dinosaur bones/ tracks	County
	Morrison Fossil Area	Jurassic	Dinosaurs	Municipal, Private
Connecticut	Dinosaur State Park	Triassic	Dinosaur tracks	State
Florida	Devils Millhopper	Miocene	Sharks teeth	State
	Ichetucknee Springs	Pleistocene	vertebrates	State
	Wakulla Springs	Pleistocene	vertebrates	State
Georgia	Sag Ponds Natural Area	Pleistocene	pollen	Private
Idaho	Hagerman Fauna Sites	Pliocene	vertebrates	National Park Service
Indiana	Ohio Coral Reef & Falls of the Ohio	Silurian-Devonian	Corals / invertebrates	State
	Hanging Rock and Wabash Reef	Silurian	coral	Private
Kansas	Monument Rocks Natural Area	Cretaceous	Marine fossils	State
Massachusetts	Gay Head Cliffs	Miocene-Pliocene	Marine fossils	Wampanoag Tribe
Mississippi	Mississippi Petrified Forest	Tertiary	Petrified logs	Private

TABLE 1. (Continued)

State	Name of NNL	Age	Type of Fossils	Ownership
Montana	Cloverly Formation Site	Cretaceous	dinosaurs	Crow Tribe
	Bridger Fossil Area	Cretaceous	dinosaurs	Bureau of Land Management
	Capitol Rock	Cretaceous thru Miocene		Forest Service
	Hell Creek Fossil Area	Cretaceous	dinosaurs	Federal, Private
	Bug Creek Fossil Area	Cret / Paleocene	dinosaurs & mammals	USFWS, B LM, Private
Nevada	Ichthyosaur Site	Triassic	Marine reptiles	Federal, State, Private
New Jersey	Riker Hill Fossil Site	Triassic	dinosaur tracks	County
New Mexico	Ghost Ranch	Triassic	*Coelophysis*	Private
New York	Fossil Coral Reef		corals	Private
	Fall Brook Gorge	Devonian	invertebrates	Private
	Petrified Sea Gardens		stromatolites	Private
South Dakota	Mammoth Site of Hot Springs	Pleistocene	vertebrates	Private
	The Castles	Cret thru Miocene	vertebrate / plants	Forest Service
Tennessee	Big Bone Cave	Pleistocene	vertebrates	State
	Lost Sea (Craighead Caverns)	Pleistocene	Jaguar tracks	Private
Texas	Palo Duro Canyon State Park	Triassic / Pliocene	vertebrates	State
	Greenwood Canyon	Cretaceous		Private
	Dinosaur Valley	Cretaceous	dinosaur tracks	State
Utah	Cleveland-Lloyd Dinosaur Quarry	Jurassic	dinosaurs	Bureau of Land Management
Virgin Islands	Vagthus Point, St. Croix	Cretaceous		Private
	Coki Point Cliffs, St. Thomas			Virgin Islands Govt., Private
Washington	Ginkgo Petrified Forest	Miocene	petrified wood	State
West Virginia	Organ Cave System	Pleistocene	vertebrates	Private
Wyoming	Bone Cabin Fossil Area	Jurassic	dinosaurs	Private
	Como Bluff	Jurassic	dinosaurs	BLM, State, Private
	Crooked Creek Natural Area			Federal

TABLE 1. (Continued)

State	Name of NNL	Age	Type of Fossils	Ownership
Wyoming	Lance Creek Fossil Area	Cretaceous	dinosaurs	Federal, State, Private
	Sand Creek	Paleocene		State, Private

TABLE 2. Websites that provide more information on some NNL's with fossils.

National Natural Landmark	Website
Anza-Borrego Desert State Park	http://parks.ca.gov/south/colorado/abdsp622.htm
Bug Creek Fossil Area	http://www.mt.blm.gov/mefo/acecweb4.html
Cleveland-Lloyd Dinosaur Quarry	http://utah.com/places/public_lands/cleveland-lloyd.htm
Dinosaur Ridge	http://www.dinoridge.org
Dinosaur Trackway	http://www.dinosaurstatepark.org/page4.html
Dinosaur Valley	http://www.tpwd.state.tx.us/park/dinosaur/dinosaur.htm
Garden Park Fossil Area	http://dinosaurdepot.com
Ghost Ranch	http://www.newmexico-ghostranch.org/museums.html
Ginkgo Petrified Forest	http://www.ohwy.com/wa/g/ginkgwsp.htm
Hagerman Fauna Sites	http://nps.gov/hafo
Hell Creek Fossil Area	http://www.mt.blm.gov/mefo/acecweb4.html
Ichthyosaur Site	http://www.state.nv.us/stparks/bi.htm
Indian Springs Trace Fossil Sites	http://www.elbert.state.co.us/cnap/NaturalAreas/NA%/20pages/indianspgstfl.htm
Lost Sea (Craighead Caverns)	http://www.thelostsea.com/home.htm
Mammoth Site of Hot Springs	http://www.mammothsite.com
Mississippi Petrified Forest	http://www.mspetrifiedforest.com
Ohio Coral Reef and Falls of the Ohio	http://www.indianaoutfitters.com/fallsohio.html
Organ Cave System	http://www.organcave.com
Palo Duro Canyon State Park	http://www.palodurocanyon.com
Petrified Sea Gardens	http://www.squonk.com/psg/main.htm
Wakulla Springs	http://www.abfla.com/parks/Wakulla/wakulla.html

Table 3. National Natural Landmarks Field Coordinators

Alaska Region

Judy Alderson
National Park Service
2525 Gambell Street
Anchorage, Alaska 99503
907-257-2448
FAX: 907-257-2448

Intermountain Region (Colorado Plateau and Rocky Mountain Clusters)

William Schreier
National Park Service
Box 170001
Bryce Canyon, Utah 84717
435-834-4108
FAX 435-834-4820

Intermountain Region (Southwestern Cluster)

Margi Brooks
Western Archeological and Conservation Center
1415 N. 6th Ave.
Tucson, Arizona 85705
520-670-6501 ext. 232

Midwest Region

Michael Gallagher
National Park Service
1709 Jackson Street
Omaha, Nebraska 68102
402-221-3418
FAX 402-221-3480

National Capitol Region

Heather Germaine
National Park Service
George Washington Memorial Parkway
c/o Turkey Run Park
McLean, Virginia 22101
703-289-2540
FAX 703-289-2546

Northeast Region (Chesapeake and Allegheny Cluster)

Michele Batcheller
National Park Service
209B Ferguson Building
University Park, Pennsylvania 16802
215-597-5199
FAX 215-597-5747

Northeast Region (New England Cluster)

Deborah Diquinzio
National Park Service
15 State Street
Boston, Massachusetts 02109-3572
617-223-5064
FAX 617-223-5097

Pacific West Region (Columbia Cascades Cluster)

Steve Gibbons
National Park Service
909 First Avenue
Seattle, Washington 98104-1060
206-220-4150
FAX 206-220-4160

Pacific West Region (Pacific Great Basin and Pacific Islands Cluster)

Jonathan Bayless
National Park Service
600 Harrison Street, Suite 600
San Francisco, California 94107
415-427-1427
FAX 415-744-4043

Southeastern Region

Chuck Schuler
National Park Service
Atlanta Federal Center
1924 Building, 100 Alabama Street, S.W.
Atlanta, Georgia 30303
404-562-3113 ext. 509
FAX 404-562-3201

Washington Office

National Park Service
1849 C Street, N.W.
Washington D.C. 20240

Craig Shafer
202-219-8934
FAX 202-208-4620

Bill Commins
202-208-4631

NNL designation carries no legal protection in itself, the formal designation has been used by concerned citizens groups as a way of providing credibility for the national significance of a specific locality and its fossil resources, and of the potential for other significant finds in the immediate area.

Ginkgo Petrified Forest State Park, near Vantage, Washington, is an NNL that was recently threatened by a proposed 231-mile cross-state oil pipeline. The proposed route of the pipeline was through the heart of one of the most significant paleontological sites in the world. Established as a National Natural Landmark in 1965, two features make Gingko Petrified Forest distinctive: the large number of genera and species (i.e. approximately 200) represented, and the unusual preservation of fossils encased in lava flows. Through the concerted efforts of numerous environmental groups, Washington State Parks, the National Park Service's NNL Program, and other extenuating circumstances, the project was headed off in time and eventually dropped.

SUMMARY

The NNL designation can be an important tool to aid in the long-term protection of fossil localities. The impact of designation is not so much determined by the government but by concerned citizens who choose to use this tool. The designation of an NNL to protect paleontological resources requires scientific documentation of the site's significance and provides a mechanism by which it's scientific significance can be translated to the general public. Designation provides a means of recognizing a site as having a level of importance that transcends its immediate area to reach national and sometimes international significance. It is a unique tool in that rather than providing do's and don'ts, it is a means of recognizing the intrinsic scientific and educational values of the site and its fossil contents.

PALEONTOLOGICAL RESOURCES MANAGEMENT, ANZA-BORREGO DESERT STATE PARK

GEORGE T. JEFFERSON
Colorado Desert District Stout Research Center, Anza-Borrego Desert State Park
200 Palm Canyon Drive, Borrego Springs, CA, 92004

ABSTRACT—Paleontologic resources in California State Parks, including both organic and mineralized remains in body or trace form, are protected, preserved, and developed for public enjoyment, interpretation, education, and scientific research. Paleontological resource management goals for Anza-Borrego Desert State Parkâ (ABDSP) are summarized as follows: (1) determine the geological, stratigraphic and geographical distribution of fossil localities and potentially fossiliferous sedimentary deposits within the ABDSP region; (2) ascertain/evaluate the significance of these resources; (3) adequately protect significant resources on site or conserve them through recovery, such that their inherent scientific and interpretive values are not degraded; (4) evaluate previous research and determine avenues of investigation needed to adequately understand, conserve and interpret the resources; (5) use the results of such research to improve management procedures and methods; (6) adequately manage and care for ABDSP paleontologic collections; (7) promote cooperative studies and management partnerships with other concerned agencies; and (8) perform and publish relevant scholarly paleontologic research.

Paleontological resources in ABDSP are widespread and exceedingly diverse, and hundreds of square miles of fossiliferous badlands terrain occur in ABDSP. Baseline GIS locality data about the distribution and concentration of these resources has been compiled from archived aerial photographs and field notes. These data, locality information derived from reconnaissance of unexplored areas, and data recovered during intensive surveys are used to direct subsequent field operations and to plan cyclic survey programs for the fossiliferous regions of the Park. A subset of these plotted data also are provided to patrol rangers for resource protection purposes. Fossils may have interpretive, historical or scientific significance. Significance must be evaluated in order to make proper decisions and take appropriate management actions which may include on site protection, recovery and conservation, and/or study and exhibition.

INTRODUCTION

Anza-Borrego Desert State Park® (ABDSP) (Acronyms used throughout the text are listed in Table 1.) encompasses over 600,000 acres of eastern San Diego County. It is the largest state park and is one of seven park units administered by the Colorado Desert District (CDD) of the Department of Parks and Recreation (DPR). DPR is organized under the California State Resources Agency whose objective is to further the conservation of California's resources. General mandates related to geological features and paleontologic remains are found in the State Public Resources Code (Division 1, Chapter 1, Article 1; Division 5, Chapter 1, Article 1, 5019.53, and Division 5, Chapter 1.7, 5097.5). Specific directions concerning identification and protection of paleontological resources are also found in the DPR Operations Manual (Section 1831(4):40 and 41). The DPR adheres to the basic content of the American Association of Museums *Code of Ethics* for museum curators, and the CDD specifically follows the Society of Vertebrate Paleontology *Statement of Ethics*.

The oldest fossils from ABDSP are Ordovician in age, over 450 million years (myr) old. However, there is a major hiatus between these and the next youngest middle Miocene remains of about 15 to 12 myr old. The most significant and abundant fossils are those of late Miocene-Pliocene terrestrial vertebrates and marine organisms, which range in age from about 7 to 4 myr ago, and Pliocene-Pleistocene terrestrial vertebrates, which date from 4 to about 0.4 myr ago.

A variety of changing environments and habitats are represented, and over 500 types of fossil plants and animals have been reported. These range from preserved microscopic plant pollen and algal spores to baleen whale bones and mammoth skeletons (Tables 2-4). Combined with the long and complete regional geologic sequence in ABDSP, these ecologically diverse fossil assemblages are an unparalleled and highly significant paleontologic resource of international importance (Webb 1998). Both the Plio-Pleistocene Epoch and the Blancan-Irvingtonian North American Land Mammal Age (NALMA) boundaries fall within the terrestrial section. These strata also record terrestrial faunal interchange between Asia and North America (taxa like *Lepus*, *Pliopotamys*, *Synaptomys*, *Mammuthus meridionalis*, *M. columbi*, Cervidae, and Ovibovinae), and from South America to North America (taxa like *Paramylodon*, *Nothrotheriops*, *Coendu*, and *Erethizon*) (Webb and Barnosky 1989).

GEOLOGIC SETTING

ABDSP lies in a unique geologic setting along the west-

TABLE 1. Acronyms

ABDSP	Anza-Borrego Desert State Parkâ
AMNH	American Museum of Natural History
BLM	Bureau of Land Management
BSF	Borrego San Felipe
CC	Coyote Canyon
CDD	Colorado Desert District
CM	Coyote Mountain
DPR	Department of Parks and Recreation
DSRC	District Stout Research Center
GIS	geographic information system
GPS	ground positioning system
IF	Imperial Formation
IVCM	Imperial Valley College Museum
LACM	Natural History Museum of Los Angeles Co.
PS	Anza-Borrego Desert SP Paleontology Soc.
UCB	University of California Berkeley
USGS	US Geological Survey
VC	Anza-Borrego Desert State Parkâ Visitor Ctr.
VCFC	Vallecito Creek-Fish Creek

ern margin of the Salton Trough. This major topographic depression forms the northernmost end of an active rift valley and continental plate boundary. The Trough extends north from the Sea of Cortez (Gulf of California) to San Gorgonio Pass, and from the eastern rim of the Peninsular Ranges east to the San Andreas Fault Zone. Over the past 9 to 10 myr, a relatively complete geologic section of over 6 km (20 k feet) of fossiliferous sediment has been deposited within ABDSP, along this rift valley's western margin.

The principal fossil-producing stratigraphic units include the Imperial Formation (IF) (Hanna 1926; Tarbet and Holman 1944; Keen and Bentson 1944; Dibblee 1954; Allen 1954; Stump 1972; Powell 1986; Remeika 1998b, 1991; also known as the Imperial Group, Remeika 1995; Winker and Kidwell 1996) and Palm Spring Formation (Woodring 1931; Tarbet and Holman 1944; Dibblee 1954; Cassiliano 1998, 1999) in the Vallecito/Fish Creek Basin (VCFC) and Coyote Mountains (CM) region, the Imperial, Palm Spring, and Ocotillo Conglomerate (Dibblee 1954; Ocotillo formation of Remeika 1992b) in the Borrego Badlands of the Borrego/San Felipe Basin (BSF), and the Bautista Formation (Frick 1921) in Coyote Canyon (CC).

The badlands exposures of these sediments cover over 160 square miles (102,400 acres) of ABDSP. Along the west side of the Salton Trough, some of these formations extend east and southeast from ABDSP, across Ocotillo Wells State Vehicular Recreation Area, and the Superstition Hills on Bureau of Land Management (BLM) property, reaching the Salton Sea. They also occur to the south in the CM and Yuha Desert, on BLM lands, and extend into Baja California del Norte, Mexico.

HISTORY AND RESEARCH

Although invertebrate fossils were reported from the Colorado Desert region in the mid-19th century (Conrad 1854, 1855; Schaeffer 1857), paleontologic investigations in what was to become ABDSP began in 1893 with the identification of fossil corals from the IF (Carrizo Creek beds) in the CM area by J. C. Merriam of the University of California, Berkeley (UCB) (Fairbanks 1893, Arnold 1904, 1906). Early in the 20th century, the invertebrate fauna from the IF, exposed in the VCFC, Alverson Canyon (also Fossil Canyon) south of CM, and BSF to the north, was the subject of investigations and numerous scientific papers by researchers with the California Academy of Sciences, California Division of Mines and Geology (then the California State Mining Bureau), California Institute of Technology, Stanford University, the UCB, University of California, Los Angeles, and the US Geological Survey (USGS) (Bowers 1901; Arnold 1904, 1906, 1909; Vaughan 1904, 1917a, 1917b; Mendenhall 1910; Kew 1914, 1920; Dickerson 1918; Hanna 1926; Hertlein and Jordan 1927).

Less attention was directed to the invertebrate fauna from the IF during the 1930's through 1950's (Grant and Gale 1931; Woodring 1931; Bramkamp 1935; Durham 1944, 1954; Tarbet and Holman 1944; Grant and Hertlein 1956; Christensen 1957), with an increase in investigations from the 1960's to the present. Researchers from ABDSP (Remeika and Fleming 1995), the University of California, Riverside (Jefferson 1966; Lasby 1969; Ballard 1971; Bauersfeld 1971; Douglas 1971; Morgan 1971; Mount 1974, 1988; Schremp 1981; Murphy 1986), the University of Chicago (Kidwell 1988; Kidwell *et al.* 1988), California State University, San Diego (Stump 1970, 1972; Stump and Stump 1972, Bell 1980; Pappajohn 1980; Dean 1988, 1996), the USGS (Powell 1987, 1995; Fleming 1993a, 1993b, 1994; Fleming and Remeika 1994; McDougal *et al.* 1994), and others (Durham and Allison 1961; Merriam and Bandy 1965; Dowlen 1969; Coble 1978; Crouch and Poag 1979; Foster 1979; Quinn and Cronin 1984; Watkins 1990a, 1990b; Tucker *et al.* 1994; Weinberg pers. comm. 1994) have continued work on invertebrates from the IF.

Vertebrate fossils were first found in ABDSP by C. Alverson and reported by Bowers (1901) 32 years before the Park was established. During the late 1930's, G. Hazen and party from the Frick Laboratory of the American Museum of Natural History (AMNH), New York, surveyed and collected in the BSF and the VCFC from 1936 through 1938. The California Institute of Technology recorded two localities in the Borrego Badlands during the mid-1930's.

During the Second World War, the Park was essentially closed and many areas were used for military exercises. Although H. Garbani discovered vertebrate fossils in the VCFC in 1940, paleontologic investigations and studies did not resume until the early mid-1950's, after he had contacted T. Downs of the Natural History Museum of Los Angeles County (LACM) (Garbani pers. comm. 1996).

H. Garbani is credited with drawing attention to the VCFC vertebrate paleontology resources and initiating the most productive phase of research in the region. This work was headed by staff and research associates of the LACM including T. Downs, L. Bessom, H. Garbani, H. Howard, G. Miller, J. White, and G. Woodard. The LACM and others continued active work focusing on the Palm Spring Forma-

FIGURE 1. Specimen Protocols and Process.

SPECIMEN DISCOVERED	VIA	⇒	INTENSIVE SURVEY CYCLIC SURVEY RESEARCH PERMIT CEQA MITIGATION PROJECT VISITOR REPORT

IS THE SPECIMEN SIGNIFICANT?

YES	NO	⇒	LEAVE IN PLACE
⇓			

ARE STAFF AND MATERIALS AVAILABLE FOR RECOVERY AND SUBSEQUENT PROCESSING?

YES	NO	⇒	STABILIZE UNTIL LATER DATE
			⇐
⇓			

CAN THE SPECIMEN BE REMOVED WITH MINIMAL ENVIRONMENTAL DISTURBANCE?

YES	NO	⇒	STABILIZE AND OBTAIN CEQA CLEARANCE (if not mitigated project)
⇓			⇐

RECOVER SPECIMEN
- ASSIGN FIELD NUMBER
- COMPLETE FIELD DATA SHEET
- COMPILE ACCESSORY FIELD DATA
- PLACE MARKER TAG ON SITE
- GPS SITE LOCATION

PREPARE SPECIMEN
- CONSERVE SPECIMEN
- COMPLETE SPECIMEN PREPARATION RECORD

CURATE SPECIMEN
- IDENTIFY AND DESCRIBE SPECIMEN
- COMPILE ALL RELATED INFORMATION AND IMAGERY IN DATA FILES
- ASSIGN PERMANENT LOCALITY NUMBER
- ASSIGN PERMANENT SPECIMEN NUMBER
- RECORD DATA AND IMAGERY IN DIGITAL DATA BASE
- GENERATE GIS DATA LAYER/S

RESEARCH AND EDUCATION/INTERPRETATION
- PERFORM RELEVANT STUDIES/RESEARCH
- CONVEY INFORMATION AND ANALYSES VIA PUBLICATION/S AND INTERPRETATION

TABLE 2. Systematic List of Fossil Plants from Anza-Borrego Desert State Park®

Explanation: † = extinct taxon; sp. = single species; spp. = two or more species present. Not all taxonomic names have been revised to conform with current usage. Higher taxonomic catagories are included where known, and common names appear in parentheses where applicable. Microfossils that comprise the Cretaceous and the Eocene age assemblages were eroded from strata on the Colorado Plateau and redeposited during Plio-Pleistocene time within the Salton Trough.

Cretaceous Floral Assemblage (Plio-Pleistocene)

Proteacidites spp. † (pollen)
Aquilapollenites spp. † (pollen)
Mancicorpus sp. † (pollen)
Tricolpites interangulus † (pollen)
Corollina sp. † (pollen)
Appendicisporites sp. † (pollen)
Cicatricosisporites sp. † (pollen)
Camarazonosporites sp. † (pollen)
Dinogymnium sp. † (pollen)
Palaeohystrichophora infusoriodes † (pollen)

Order indeterminate
Family indeterminate
Genera and species indeterminate (dynoflagellates and spores)

Eocene Floral Assemblage (Plio-Pleistocene)

Pistillipollenites sp. cf. *P. mcgregorii* † (pollen)

Fish Creek Gypsum Floral Assemblage (late Miocene)

Hystrichokolpoma rigaudae (dinoflagellate)
Operculodinium centrocarpum (dinoflagellate)
Tectatodinium sp. (dinoflagellate)
Spiniferites ramosus (dinoflagellate)
Selenophix sp. (dinoflagellate)
Genera and species indeterminate (dinoflagellates)

Class Gymnospermae

Order Coniferales
Family Cupressaceae
Genus and species indeterminate (cypress, cedar or juniper)
Family Taxodiaceae
Genus and species indeterminate (redwoods or sequoia)
Family Pinaceae
Genus and species indeterminate (pine or spruce)
Family Ephedraceae
Ephedripites sp. † (joint-fir)

Class Angiospermae
Subclass Dicotyledones

Order Fagales
Family Juglandaceae
Juglanspollenites sp. † (walnut)

TABLE 2. (Continued)

- Order Malvales
  - Family Malvaceae
    - Genus and species indeterminate (mallow)
- Order Asterales
  - Family Asteraceae
    - Genus and species indeterminate (sunflower)
- Order Myrtales
  - Family Onagraceae
    - Genus and species indeterminate (evening-primrose)

Carrizo Local Flora (Plio-Pleistocene)

Class Gymnospermae

- Order Coniferales
  - Family Cupressaceae
    - Genus and species indeterminate (cypress, cedar or juniper)
  - Family Pinaceae
    - *Picea* spp. (spruce)

Class Angiospermae
Subclass Dicotyledones

- Order Laurales
  - Family Lauraceae
    - *Persea coalingensis* † (avocado)
    - *Umbellularia* sp. ? *U. salicifolia* † (bay-laurel)
- Order Malpighales
  - Family Salicaceae
    - *Populus alexanderi* H (Alexander's cottonwood)
    - *Salix* sp. (willow)
    - *Salix gooddingii* (Gooding's willow)
- Order Lamiales
  - Family Oleaceae
    - *Fraxinus velutina* (ash)
- Order Fagales
  - Family Juglandaceae
    - *Juglans pseudomorpha* † (walnut)
- Order Sapindales
  - Family Sapindaceae
    - *Aesculus* sp. (buckeye)

Subclass Monocotyledones

- Order Arecales
  - Family Arecaceae
    - *Sabal* sp. cf. *S. miocenica* † (Miocene sabal palm)
    - Genus and species indeterminate (palm)

Fresh Water Flora (Plio-Pleistocene)

- *Pediastrum* spp. (algal phytoplankton)
- *Scenedesmus* spp. (algal phytoplankton)
- *Chara* sp. (macrophytic algae)

tion in the VCFC through the 1980's (Downs 1957, 1965, 1966, 1967; Brattstrom 1961; Downs and Woodard 1961a, 1961b; White and Downs 1961, 1965; Howard 1963, 1972a, 1972b; White 1964, 1965, 1968, 1969, 1970, 1984, 1991; Downs and White 1965a, 1965b, 1966, 1968; Zakrezewski 1972; Becker and White 1981; Hutchison 1987; Jefferson 1989; Martin and Prince 1989; Norell 1989; Downs and Miller 1994).

In the early 1970's, G. Miller of Imperial Valley College, began an active and productive collection and curation program of ABDSP vertebrate fossils. Most of these collections were conserved at the Imperial Valley College Museum (IVCM), and were the subject of research and publications (Miller 1977a, 1977b, 1979, 1985a, 1985b; Miller *et al.* 1982, 1988, 1989, 1991; Parks *et al.* 1989; Downs and Miller 1994). Vertebrate fossils were also housed at the ABDSP Visitor Center (VC), which opened in 1979. In 1982, preparation of paleontologic materials largely shifted from the VC to the Stout Paleontology Laboratory at Park headquarters. With the death of G. Miller in 1989, paleontology projects at the IVCM were scaled down, and for the following several years, the program was supervised by J. White of the University of Arizona, Tucson and B. Stout of Anza-Borrego Desert Natural History Association and the Desert Research Institute, Reno, Nevada. Important graduate research on the vertebrate faunas were supervised by J. White, including Cunningham (1984), Cassiliano (1994), and Blackford (1995).

In 1991, ABDSP staff assembled a Paleontology Advisory Board consisting of paleontologists and museum professionals from institutions throughout the western US to provide recommendations and direction in the management of ABDSP paleontologic resources. At the suggestion of the Board, IVCM collections were transferred to ABDSP in 1992, and the LACM vertebrate collections, recovered under State permits from ABDSP, were transferred to ABDSP in 1997. G. Jefferson was hired as CDD Paleontologist in 1994.

Construction of the CDD Stout Research Center (DSRC), which houses a research library and conserves not only the above paleontologic collections but natural history, historic and archaeologic collections, was completed in 1999. The paleontological library holdings, with over 15,000 separates, is an important resource for management and research, and includes the combined collections of G. Jefferson, G. J. Miller, and John A. White. The DSRC facilitates a variety of museum and university research projects and cooperative resource management programs that are supported by both private and agency funds. The ABDSP Paleontology Society (PS) was formed in 1993 to assist CDD staff in managing paleontological resources and collections. Members of this volunteer group are trained to professional standards and State certified in field surveying, specimen preparation, and curation activities.

ABDSP/CDD staff and others have continued research and publication on ABDSP fossils (Remeika *et al.* 1986; Remeika and Fleming 1995; Remeika 1988, 1991, 1992b, 1997a, 1997b; Stout and Remeika 1991; Martin 1993; Remeika and Jefferson 1993; Stewart and Roeder 1993; Cassiliano 1994; Jefferson 1994, 1995a, 1995b, 1999a; Jefferson and Tejada-Flores 1995; Jefferson *et al*. 1995; McDonald *et al.* 1996; Murray and Jefferson 1996; Remeika and Beske-Dehl 1996; McDaniel and Jefferson 1997, 1999a, 1999b, 2000; Jass 1998; Campbell *et al*. 1999; Jolly 2000). The late Tertiary and Quaternary paleontology of ABDSP was recently summarized (Remeika *et al.* 1995; Remeika 1998b), and the taphonomy and biostratigraphy of the mammalian fossils from the VCFC recently described (Cassiliano 1997, 1998, 1999).

PALEONTOLOGICAL RESOURCES

The oldest reported fossils from ABDSP area are conodonts of early Ordovician age, *ca.* 450 myr (Dockum and Miller 1982; Miller and Dockum 1983) (Table 4). These tooth-like structures from agnathan vertebrates occur in the marine metasediments east of Carrizo Mountain. Miller and Dockum (1983) correlate these deposits with those of the Santa Rosa Formation (also see Mueller and Condie 1964) in the Santa Rosa Mountains, north and northeast of Clark Dry Lake.

Cretaceous plant pollen, spores and dinoflagellates (Fleming 1993a, 1993b, 1994; Fleming and Remeika 1994; Remeika and Fleming 1994, 1995) (Table 2) are known from Pliocene formations in the VCFC. These microfossils have been eroded from Mesozoic age strata on the Colorado Plateau and transported by the ancestral Colorado River into the Salton Trough. Seven taxa of reworked Cretaceous foraminifera (Table 3) have been identified from the same units (Merriam and Bandy 1965). Also, reworked Eocene plant microfossils have been described from the VCFC (Fleming 1993a, 1993b, 1994; Fleming and Remeika 1994; Remeika and Fleming 1994, 1995).

A diverse variety of invertebrates has been recovered from the IF in the VCFC and CM (Hanna 1926; Douglas 1971; Stump 1970, 1972; Stump and Stump 1972; Powell 1984; Dean 1988, 1996; Mount 1988) (Table 2, 3). These organisms include calcareous nanoplankton and dinoflagellates (Dean 1988, 1996), plant pollen and spores (Dean 1988, 1996), foraminifera (Tarbet and Holman 1944; Durham and Allison 1961; Ingle 1974; Crough and Poag 1979; Quinn and Cronin 1984), sponges (Dowlen 1969), corals (Vaughan 1904, 1917a, 1917b; Dowlen 1969; Foster 1979), polychaeta (Dowlen 1969), bivalves (Arnold 1906; Dickerson 1918; Powell 1986, 1987), gastropods (Dickerson 1918; Powell 1986, 1987), echinoderms (Kew 1914, 1920; Grant and Hertlein 1956; Powell 1995), and crustaceans (Dowlen 1969; Quinn and Cronin 1984; Tucker *et al.* 1994) (Table 3). Many of these forms are related to Caribbean species, and represent a time several myr prior to the emergence of the Isthmus of Panama (Arnold 1904; Mount 1974; Foster 1979; Quinn and Cronin 1984; McDougal *et al*. 1994).

In many areas, marine invertebrate fossil remains are well preserved and abundant. Carbonate platform, outer and inner shelf, near shore and estuarine/brackish depositional marine environments are represented (Arnold 1909; Ingle

TABLE 3. Systematic List of Fossil Invertebrates from the Anza-Borrego Desert State Parkâ Region

Explanation: ♦ = holotypic specimen; ☦ = extinct taxon; sp. = single species; spp. = two or more species present. Not all taxonomic names have been revised to conform with current usage. Higher taxonomic catagories are included where known, and common names are provided where known. Subgenera and subspecies are not listed. Microfossils that comprise the Cretaceous age assemblage were eroded from the Colorado Plateau and redeposited within the Salton Trough during Plio-Pleistocene time.

Paleozoic Molluscs
(? Mississippian)

Phylum Mollusca (marine clams and snails)

Order indeterminate
Family indeterminate
Genus and species indeterminate

Cretaceous Microfossils
(Plio-Pleistocene)

Phylum Protozoa
Class Sarcodina (foraminifers)

Globotruncana globigerinoides ☦
Globigerinelloides aspera ☦
Heterohelix globulosa ☦
H. reussi ☦
H. striata ☦
Neobulimina canadensis ☦
Pseudouvigerina cretacea ☦

Fish Creek Gypsum Assemblage
(late Miocene)

Braarudosphaera bigelowii (calcareous nannoplankton)
Calcidiscus macintyrei (calcareous nannoplankton)
Coccolithus pelagicus (calcareous nannoplankton)
Crenalithus doronicoides (?) (calcareous nannoplankton)
Dictyococcittes scrippsae (?) (calcareous nannoplankton)
D. minutes (calcareous nannoplankton)
Helicopontosphaera kamptnen (calcareous nannoplankton)
Reticulofenestra pseudoumbilica (calcareous nannoplankton)
Spenolithus abies (calcareous nannoplankton)
S. moriformis (calcareous nannoplankton)

Imperial Formation Western Salton Trough
Coyote Mountain and Vallecito/Fish Creek Basin Assemblages
(late Miocene)

Phylum Protozoa
Class Sarcodina (formaninfers)

Order Foraminifera
Family Rotalidae
Siphonina pulchra
Family Amphisteginidae
Amphistegina gibbosa
A. lessoni
Family Miliolidae
Quinqueloculina sp.

Family Buliminidae
Bolivina interjuncta
B. subaenariensis mexicana
B. vaughani
Reusella pacifica
Uvigerina peregrina
Trifarina bella
T. angulosa
Cassidulina delicata
C. laevigata
C. subglobssa
Cassidulina tortuosa
Family Anomalinidae
Cibicides fletcheri
Hanzawaia nitidula
H. basiloba
Planulina ornata
Family Globigerinidae
"Globigerina pachyderma"
G. quinqualoba
Family Nonionidae
Elphidium gunteri
Elphidium sp.
Nonion basispinata
N. miocenica stella
N. glabratalia californica
Family Textulariidae
Textularia schencki
Textularia spp.
Family **
Ammonia beccarii
Ammonia sp. cf. *A. parkinsonia*
Planorbulina acervalis
Sphaeroidinella subdhiscens
Globigerinita uvula
Epistominella subperuviana

Phylum Coelenterata
Class Anthozoa
Subclass Zoantharia (corals)

Order Scleractinia
Family Siderastreidae (starlet corals)
Siderastrea californica ♦ ☨
S. mendenhalli ♦ ☨
Family Astrocoeniidae (star corals)
Stephanocoenia fairbanksi
Family Faviidae
Solenastrea faribanksi ♦ ☨
Pleisiastrea californica
Diploria bowseri
Family Poritidae (finger corals)
Porites carrizensis ♦ ☨
Family Rhizangiidae (= Astrangiidae)
Astrangia haimei
Family Menadrinidae (starlet and brain corals)
Meandrina bowseri ♦ ☨
Dichocaenia merriami ♦ ☨
Family Caryophyllidae (flower corals)
Eusmilia carrizensis ♦ ☨
Eusmilia solida ☨

Phylum Mollusca
Class Bivalvia (marine clams)

Order Protobranchia
Family Nuculidae (nut clams)
Nucula sp.

Order Prionodontida
- Family Arcidae (ark clams)
  - *Arca pacifica*
  - *Barbatia reeveana*
  - *Anadara carrizoensis* ♦ †
  - *A. formosa*
  - *A. multicostata*
  - *A. reinharti*
  - *Anadera* sp. (nov.) A †
  - *Anadera* sp. (nov.) B †
  - *Scapharca* sp. (nov.) †
- Family Glycymerididae (bittersweet clams)
  - *Glycymeris bioclor*
  - *G. gigantea*
  - *G. maculata*
  - *G. multicostata*

Order Pteroconchida
- Family Pinnidae (pen clams)
  - *Atrina stephensoni*
  - *Pinna latrania* ♦ †
  - *P. mendenhalli* ♦ †
  - *Pinna* sp. (nov.) †
  - *Atrina stephensi* ♦ †
  - *Atrina* n. sp. aff. *A. pectinata* †
- Family Mytilidae (date mussels)
  - cf. *Lithophaga attenuata*
  - *Lithophaga* sp. aff. *L. plumula* (rockboring mussel)
- Family Ostreidae (oysters)
  - *Myrakeena* sp. ? *M. angelica*
  - *Dendostrea*? *vespertina* †
  - *Dendostera folium*
  - *Ostreacalifornica* †
  - *O. fischeri*
  - *O. haitensis*
  - *O. iridescens*
  - *O. palmula*
  - *O. serra*
  - *Undulosa megodon*
  - *Saccostrea palmeri*
- Family Gryphaeidae (oysters)
  - *Pycnodonte heermanni* †
- Family Pectinidae (scallops)
  - *Argopecten abietis* †
  - *A. deserti* ♦ †
  - *A. mendenhalli* †
  - *A. sverdrupi* †
  - *Chlamys antonitaensis* †
  - *C. circularis*
  - *C. corteziana* †
  - *C. revellei* †
  - *C. estrellanus* †
  - *C. mediacostata* †
  - *C. subnodosus*
  - *Euvola keepi* †
  - *Fabellipecten carrizoensis* ♦ †
  - *Leptopecten bakeri* †
  - *L. subnodosus*
  - *Patinopecten dilleri*
  - *Pecten vogdesi*

Family Astropectinidae (scallops)
Astropecten sp.
Family Plicatulidae
Plicatula inezana
P. spondylopsis
Family Spondylidae (spiny osters)
Spondylus bostrythes †
S. calcifer
S. victoriae
Spondylus sp. (nov.) †
Family Anomiidae (jingles)
Anomia peruviana (pearly jingle)
A. subcostata †
Placunanomia hannibali
Family Limidae (file shells)
Limaria sp. †
Order Eulamellibranchia
Family Chamidae (chamas)
Chama frondosa
C. pellucida (agate chama)
Arcinella arcinella
A. californica
Order Heterodontida
Family Lucinidae (lucine clams)
Callucina sp. †
Codakia distinguenda
Linga sp. (nov.) †
Miltha xantusi
Pegophysema edentuloides
Pegophysema sp. cf. *P. spherica* †
Divalinga eburnea
Family Corbulidae
Corbula sp. (nov.) †
Family Crassatellidae (crasstellas)
Eucrassatella digueti
E. subgibbosus †
Family Carditidae (carditas)
Cardites crassicostata
C. megastropha
Cardites sp. (nov.) †
Carditamera laticostata
C. tricolor
Family Cardiidae (cockles or heart clams)
Trigoniocardia sp. aff. *T. guanacastense*
Laevicardium sp.
Family Tellinidae (tellens)
Tellina ulloana
Psammotreya dombei
P. ochracea
Family Donacidae (bean or wedge clams)
Donax sp. cf. *D. gracilis*
Family Semelidae (semele clams)
Semele bicolor
Family Solencurtidae (jacknife clams)
Tagelus californianus (California jacknife clam)
T. violascens
Family Corbiculidae
Polymesoda notabilis
Family Veneridae (Venus clams)
Chione californiensis (banded chione)
Dosinia dunkeri
D. ponderosa
Irus oblongus
Megaptaria squalida
Periglypta multicostata
Pitar sp. ? *P. catharius*

Ventricolaria isocardia
Family Haitellidae (geoducks)
Panopea abrupta
P. generosa
Family Pholadidae (rock piddocks)
Cryptopleura costata
Family Thraciidae (thracia clams)
Cyathodonta undulata
Cyathodonta sp. aff. C. dubiosa

Class Gastropoda (marine snails)

Order Vetigastropoda
Family Haliotidae (abalones)
Haliotis sp.
Order Diotocardia
Family Patellacea (= Acmaeidae) (limpets)
Acmaea sp. (nov.) ✝
Family Fissurellidae (= Scissurellidae) (keyhole limpets)
Diodora alta
Fissurella sp.
Family Turbinidae (turban snails)
Turbo magnificum (*** ? magnifuscum*)
Turbo sp.
Family Trochidae (top snails)
Calliostoma bonita
Tegula marina
Order Monocardia
Family Nertidae (nerites)
Nerita scabricosta (*** ? scabricostata*)
N. funiculata
Family Littorinidae (periwinkles)
Littorina varia
Family Architectonicidae (sundials)
Architectonica nobilis
Family Turritellidae (tower snails)
Turritella imperalis ♦ ✝
T. goniostoma
Vermicularia pellucida
Family Potamididae (horn snails)
Cerithidea ineisum
C. mazatlanica
Family Cerithiidae (ceriths)
Liocerithium judithae
Family Hipponicidae (hores-hoof limpets)
Cheilea equestris
Hipponix panamensis
Family Clyptraeidae (cup and saucer snails)
Crepidula onyx
Crucibulum scutelatum
C. spinosum
Family Naticidae (moon snails)
Natica chemnitzii
N. unifasciata
Polinices bifasciatus
P. recluzianus
P. uber
Family Tonnidae (tuns)
Malea ringens
Family Cypraeidae (cowries)
Cypraea cervinetta
C. amandusi
C. imperalis (nov.) ✝
Family Strombidae (conchs)
Strombus galeatus
S. gracilior
S. granulatus
S. obliteratus
Family Cassidae (helmet snails)
Cassis subtuberosus ♦ ✝

Family Ficidae (fig snails)
Ficus ventricosa
Family Cymatiidae (distorsio snails)
Distorsio constricta (** ? *Distorsic constricta*)
Family Muricidae (murex snails)
Hexaplex brassica
H. erythrostomus
Family Melongenidae (melondenid welks)
Melongena patula
Family Fascolariidae (tulip snails)
Fascolaria princeps
Latrius concentricus
Leucozonia cerata
Family Pyrenidae
Strombina solidula
Family Cancellariidae (nutmeg snails)
Cancellaria cassidiformis
C. coronadoensis
C. obesa
C. urceolata
Family Olividae (olive snails)
Oliva spicata
Olivella gracilis
Family Turbinellidae (vase snails)
Vasum pufferi
Family Mitridae (miter snails)
Mitra crenata
Subcancilla longa
S. sulcata
Family Burrinidae (welks)
Solenosteira anomala
Family Modulidae
Modulus catenulatus
M. unidens
Family Conidae (cone snails)
Conus arcuatus
C. bramkampi
C. californicus
C. gladiator
C. gradatus
C. fergusoni
C. regularis
C. planiliratus
Family Turridae (turrid snails)
Knefastia olivacea
Polystira oxytropis
Family Terebridae (auger snails)
Terebra dislocata
T. elata
T. gausapata
T. protexta
T. robusta
T. wolfgangi
Order Tectibranchiata
Family Bullidae (bubble snails)
Bulla punctulata
B. striatus
Order **
Family **
? *Batillana* sp.

Phylum Echinodermata
Class Stelleroidea (star fishes)

Order indeterminate
Family indeterminate
Genus and species indeterminate

Class Echinoidea (sea urchins and sand dollars)

Family Cidaridae (sea urchins)
Cidaris sp.
? *Eucidaris thouarsii*

Family Diadematidae (sea urchins)
Centro stephanus
Family Arbaciidae (sea urchins)
Arbacia incisa
Family Toxopneustidae (sea urchins)
Lytechinus sp. cf. *L. anamesus*
Toxopneustes sp. cf. *T. roseus*
Tripneustes californicus †
Family Echinoneidae (sea urchins)
Echinoneus burgeri
Family Strongylocentrotidae (= Echinometridae) (sea urchins)
Strongylocentrotus purpuratus
Family Clypeastridae (sea urchins)
Clypeaster bowseri †
C. carrizoensis ♦ †
C. deserti ♦ †
C. subdepressus
Clypeaster sp. cf. *C. rotundus*
Family Mellitidae (= Scutellidae) (sand dollar)
Encope arcensis †
E. sverdrupi †
E. tenuis †
Encope morlini (nov.) †
Family Schizasteridae (= Hemiasteridae) (sea urchins)
Agassizia scrobiculata
Agassizia sp. A
Schizaster morlini †
Family Brissidae (= in part Spatangidae) (sea urchins)
Brissus obesus
Metalia spatagus
Family Loveniidae (= in part Spatangidae) (sea urchins)
Lovenia sp. cf. *L. hemphilli*

Phylum Bryozoa
Class Gymnolaemata (bryozoans)

Order Cheilostomata
Conopeum commensale

Phylum Arthropoda
Class Crustacea

Order Cirripeda
Family Balanidae
Balanus tintinnabulum (acorn barnacle)

Subclass Ostracoda (marine water fleas)

Order Podocopida
Purina sp.
Hermanites sp.
Loxocorniculum sp.
Xestoleberis sp.
Anterocythere sp.
Cytheura sp.
Microcytherua sp.
Loxoconcha sp.
? *Aurila* sp.
? *Anterocythere* sp.
Perissocytheridea sp.
? *Ambostracon* sp.
Caudites sp.

Typanites Marine Ichnofauna (borings and tracks)
(late Miocene)

Entobia (clionid sponge boring)
cf. *Gastrochaenolites torpedo* (clam boring)
Maeandro polydora (polychaete worm boring)
Typanites (polychaete worm or barnacle boring)
Echinoid (borings)

Fresh Water Lacustrine Assemblage
(Plio-Pleistocene)

Phylum Mollusca
Class Bivalvia (fresh water clams)

Order Schizodonta
- Family Unionidae
  - *Anodonta californiensis*

Order Heterodonta
- Family Sphaeriidae
  - *Pisidium compressum*
- Family Mactridae
  - *Rangia lecontei* ♦ ✝

Class Gastropoda (fresh water snails)

Order Megagastropoda
- Family Amnicolidae
  - *Paludestrina* sp.
- Family Hydrobiidae
  - *Fontelicella longinqua*
- Family Littorinidae
  - *Tyronia* sp.

Order Basommatophora
- Family Physidae
  - *Physa humerosa*
  - *P. virgata*
- Family Lymnaeidae
  - *Bakerilymnaea techella*
- Family Planorbidae
  - *Gyralus parvus*
  - *Planobella tenuis*
  - *Bannerillus* sp.
- Family Zonitidae
  - *Zanitoides arborreus*

Phylum Arthropoda
Class Crustacea
Subclass Ostracoda (fresh water fleas)

Order Podocopia
- *Limmocythere* sp.
- *Candona* sp.
- *Ilyocypris* sp.
- ? *Lineocypris* sp.

Notes: New names (nov.) of Stump (1972) and Powell (1986) remain informal. ** = missing taxonomic information or possible errors.

1974; Coble 1978; Bell 1980; Bell-Countryman 1984; Quinn and Cronin 1984; Richardson 1984; Watkins 1990b). The latter is typified by thick channel deposits of predominately oyster and pecten shell coquina (Watkins 1990a).

The IF also yields fossil marine vertebrates (Mitchell 1961; Deméré 1993; Thomas and Barnes 1993). The taxa represented include sharks and rays, bony fish, baleen whale, walrus, and dugong (Table 4).

The Pliocene age, Carrizo Local Flora (Remeika *et al.* 1988; Remeika 1994; Remeika and Fleming 1995) includes a palm, a cupressid, and deciduous hardwoods (Table 2). Charaphytes are also known from the fresh water deposits of the Palm Spring Formation in the VCFC. Mid to late Pleistocene fossil woods also have been recovered from the Ocotillo Conglomerate and Bautista Formation in the BSF (Remeika pers. comm. 1996).

Lacustrine and fluvial fresh water invertebrates (Table 3) have been recovered from the Borrego, Brawley (Tarbet and Holman 1944; Durham 1950; Dibblee 1954), and Bautista Formations (Frick 1921; Remeika pers. comm. 1996; Gensler pers. comm. 2001), in the BSF (Remeika pers. comm. 1996), and Palm Spring Formation, in the VCFC (Taylor 1966, pers. comm. 1976, 1977, 1982). The identified taxa include bivalves, gastropods, and ostracodes (Sohn pers. comm. 1961; Quinn and Cronin 1984; Steinmetz pers. comm. 1998) (Table 3).

The oldest terrestrial vertebrates within ABDSP are from the Borrego Buttes. The remains, which include a gomphothere or paleomastodon, pseudaelurine felid and small stilt-legged camelid (Table 3), were recovered from near shore lacustrine deposits (Jefferson 1999a). The strata are thought to correlate with the Split Mountain Formation (Woodard 1963, 1974; Kerr *et al.* 1979; Winker 1987; Cassiliano 1994) that occurs below the base of the Imperial Formation. They predate the Fish Creek Gypsum, and fall in a 12-9 myr age range (Dean 1988, 1996; Kerr and Abbott 1996; Jefferson 1999a).

The late Miocene through mid-Pleistocene Layer Cake, Arroyo Seco, and Vallecito Creek vertebrate assemblages occur in a superposed, conformable biochronologic sequence (see Remeika *et al.* 1995, and Cassiliano 1999). The Layer Cake assemblage (Hemphillian and early Blancan NALMA) falls within the Gilbert Magnetochron, and ranges between about 4.0 and 3.4 Ma. The Arroyo Seco assemblage (mid-Blancan NALMA) directly follows the Layer Cake assemblage at about 3.4 Ma. Volcanic ash fission track analyses (Johnson *et al.*1983) place the transition between the Arroyo Seco assemblage and the following Vallecito Creek assemblage before the end of the Gauss Magnetochron at 2.3 + 0.4 Ma. The Vallecito Creek assemblage (late Blancan through mid-Irvingtonian NALMA) falls within the Matuyama Magnetochron, and ranges from the base of the Matuyama to the Jaramillo Magnetosubchron, or from about 2.3 to 0.9 Ma. For a discussion of the VCFC faunal sequence and chronology, see Downs and White (1968), Johnson *et al*. (1975), Opdyke *et al.* (1974, 1979), Lindsay, *et al.* (1987), Lundelius, *et al*. (1987), Lindsay and White (1993), Remeika *et al.* (1995), and Cassiliano (1999).

The Borrego LF (Remeika and Jefferson 1993) (Irvingtonian NALMA) ranges in age from about 1.25 to as young or younger than 0.37 Ma (Remeika and Beske-Dehl 1996, 1998a). It overlaps chronologically with the upper range of the Vallecito Creek assemblage, and falls within the Matuyama and Brunhes Magnetochrons. The stratigraphic section also includes the Bishop Tuff, dated at about 0.76 Ma (Rymer 1991).

COLLECTIONS AND ARCHIVAL DATA

The CDD paleontology core collections consist of paleobiologic specimens acquired and conserved because of their scientific significance and educational value. Collections facility and curatorial standards are maintained in compliance with State *Museum Collections Management Handbook* (1998, 2000). Fossil plants, marine and fresh water invertebrates, and vertebrates are conserved at the DSRC. Each group, for example plants or vertebrates, is organized internally by local assemblages (= stratigraphic and/or geographic divisions), locality number, and specimen number (see Murray 1996). On-going paleontologic research and active resource management practices result in an annual increase of about 0.2 % in the number of prepared and catalogued specimens.

Primary specimen and locality data (up to 86 data fields) for the vertebrates presently reside in the State-wide *Argus* museum collections data system in Sacramento. It is directly accessed via telephone link from the DSRC. Botanic and invertebrate fossil data are maintained at the DSRC in *Access*. The DSRC also houses archival data that include original field notes, annotated topographic maps, aerial photographs and digital maps, both digital and standard photographs of sites and specimens, standard DSRC locality data sheets (in data base field format), specimen preparation records, original catalogue card files (IVCM) and digital catalogues (IVCM, LACM), research notes, correspondence, and reports and publications. Over 1,000 vertebrate specimens have been described in formal publications and/or gray literature.

Vertebrate paleontologic locality point data, previously recorded by ABDSP, IVCM and LACM on US Department of Agriculture (1953) aerial photographs were captured digitally as GIS point layers that include over 2.4 k localities. The points are annotated with institutional acronyms and locality numbers, permitting the linkage of locational or taxonomic information from any nested set of data fields within the database. These data can be combined with topographic contours, roads and trails, and/or digital orthoquadrangle shaded topography, and printed at any scale for field survey and reporting purposes. Locality data are considered highly sensitive proprietary information which are made available only to qualified researchers through a permit process.

Marine invertebrates recovered from the IF in the CM and VCFC, fresh water invertebrates from formations in the BSF and VCFC, and fossil woods from the BSF and VCFC comprise the core of the plant and invertebrate collections. Locality numbers for fossil invertebrate specimens recovered regionally from the IF that are housed at other institutions (California Academy of Sciences, San Francisco; California State University, San Diego; Imperial Valley Archaeological Museum, El Centro/Ocotillo; Milwaukee Public Museum, Wisconsin; LACM, Invertebrate Paleontology and Vertebrate Paleontology Sections; San Diego Museum of Natural History; San Diego State University; University of California, Berkeley, Museum of Paleontology; University of California, Los Angeles, Department of Geology; University of California, Riverside, Department of Geological Sciences; USGS) have been compiled as a research aid. Much of the material obtained by the above institutions was collected before ABDSP became a State Park.

The AMNH collection of fossil vertebrates was acquired prior to the use of State collecting permits. Also, portions of the BSF and VCFC were not part of the Park in 1936/1937.

TABLE 4. **Systematic List of Fossil Vertebrates from Anza-Borrego Desert State Parkâ Region**

Explanation: ¨ = holotypic specimen; ? = extinct taxon; sp. = single species; spp. = two or more species present. Taxonomic names have been revised to conform with current usage, and common names are provided in parentheses where applicable.

Santa Rosa Metamorphics Assemblage (Ordovician)

"Class" Conodonta ("agnathan fish")

Paltodus sp. ? *P. spurius*
Paltodus sp. ? *P. bassleri*
"*Scolopodus*" sp. ? "*S.*" *quadraplicatus*
? *Ulrichodina* sp.

Imperial Formation Marine Assemblage (late Miocene)

Class Chrondricthyes (sharks, skates, and rays)

Order Galeomorpha
- Family Cetorhinidae
  - *Cetorhinus* sp. (basking sharks)
- Family Carcharinidae
  - *Carcharodon carcharias* (white shark)
  - *Galeocerdo rosaliensis* (shark)
  - *Hemipristus serra* (shark)

Order Batoidea
- Family Myliobatidae
  - Genus and species indeterminate (eagle rays)

Class Osteichthyes (bony fish)

Order Culpeiformes
- Family Culpeidae
  - Genus and species indeterminate (herrings)

Order Syngnathiformes
- Family Syngnathidae
  - *Hipposyngnathus imporcitor* (sea horse)

Class Reptilia (reptiles)

Order Testudines
- Family Chelonidae
  - Genus and species indeterminate (sea turtles)

Class Mammalia (mammals)

Order Carnivora
- Family Odobenidae
  - *Valenictus imperialensis* ♦ ✝ (Imperial walrus)

Order Sirenia
- Family Dugongidae
  - Genus and species indeterminate (dugong)

Order Ctacea
- Family Balaenopteridae
  - Genus and species indeterminate (baleen whale)
- Family Cetotheriidae
  - Genus and species indeterminate (whale-bone whale)

Fish Creek, Vallecito Creek, and Borrego Terrestrial Assemblages (Plio-Pleistocene)

Class Osteichthyes (bony fish)

Order Salmoniformes
- Family Salmonidae
  - ? *Salmo* sp. (trouts and salmons)

Order Cypriniformes

Family Catostomidae
Genus and species indeterminate (minnow, stickleback, or sucker)
Xyrauchen sp. cf. *X. texanus* (humpback sucker)

Class Amphibia (amphibians)

Order Anura
Family Bufonidae
Bufo sp. (toads)
Family Ranidae
Rana sp. (frogs)

Class Reptilia (reptiles)

Order Testudines
Family Kinosternidae
Kinosternon sp. (mud turtles)
Family Testudinidae
Geochelone sp. (giant tortoises)
Gopherus agassizii (desert tortoise)
Family Chelonidae
Genus and species indeterminate (sea turtles)
Family Emydidae
Clemmys marmorata (western pond turtle)
Trachemys scripta (common slider)
Order Squamata
Suborder Lacertilia
Family Iguanidae
Callisaurus sp. (zebra-tailed lizards)
Crotaphytus sp. (collared lizards)
Dipsosaurus dorsalis (desert iguana)
Gambelia corona ♦ ✝ (crowned leopard lizard)
Iguana iguana (green iguana)
Phrynosoma sp. (horned lizard)
Phrynosoma anzaense ♦ ✝ (Anza horned lizard)
Pumilia novaceki ♦ ✝ (Novacek's small iguana)
Sceloporus sp. A (spiny lizard)
Sceloporus sp. B (spiny lizard)
Sceloporus magister (desert spiny lizard)
Uta stansburiana (side-blotched lizard)
Family Teiidae
Ameiva sp. or *Cnemidophorus* sp. (ground lizard or whiptail)
Cnemidophorus tigris (western whiptail)
Family Scincidae
Eumeces sp. (skinks)
Family Xantusiidae
Xantusia downsi ♦ ✝ (Downs' night lizard)
X. vigilis (desert night lizard)
Family Anguidae
Gerrhonotus multicarinatus (southern alligator lizard)
Suborder Serpentes
Family Colubridae
Hypsiglena sp. (night snakes)
Lampropeltis getulus (common king snake)
Masticophis flagellum (coachwhip snake)
Thamnophis sp. (garter snakes)
Family Crotalidae
Crotalus sp. (rattlesnakes)

Class Aves (birds)

Order Gaviformes
Family Gaviidae
Gavia sp. (loons)
Order Podicipediformes
Family Podicipedidae
Aechmophorus occidentalis (western grebe)
Podiceps sp. (grebes)
Podiceps nigricollis (eared grebe)
Order Procellariiformes
Family Procellariidae
Puffinus sp. (shearwaters)

Order Pelecaniformes
- Family Pelecanidae
  - *Pelecanus* sp. cf. *P. erythrorhynchos* (white pelican)

Order Ciconiiformes
- Family Teratornithidae
  - *Aiolornis incredibilis* † (incredible teratorn)
- Family Vulturidae (Cathartidae)
  - *Cathartes aura* (turkey vulture)
  - *Gymnogyps* sp. (condors)

Order Pheonicopteriformes
- Family Pheonicopteridae
  - *Phoenicopterus* sp. (flamingos)

Order Anseriformes
- Family Anatidae
  - *Aix* sp. ? *A. sponsa* (wood duck)
  - *Anas* sp. ? *A. acuta* (pintail duck)
  - *A. clypeata* (shoveller duck)
  - *Anser* sp. (large goose)
  - *Branta* sp. cf. *B. canadensis* (Canada goose)
  - *Brantadorna downsi* ♦ † (Downs' gadwall duck)
  - *Bucephala fossilis* ♦ † (fossil goldeneye)
  - *Chen rossii* (Ross' goose) or *Branta bernicula* (brant)
  - *Cygnus* sp. ? *C. paloregonus* † (Oregon swan)
  - ? *Lophodytes cucullatus* (hooded merganser)
  - *Melanitta* sp. ? *M. persipicillata* (surf scoter)
  - *Mergus* sp. (mergansers)
  - *Oxyura bessomi* ♦ † (Bessom's stiff-tailed duck)
  - *O. jamaicensis* (ruddy duck)

Order Accipitriformes
- Family Accipitridae
  - *Accipiter cooperii* (Cooper's hawk)
  - *A. striatus* (sharp-shinned hawk)
  - *Aquila* sp. ? *A. chrysaëtos* (golden eagle)
  - *Buteo sp. cf. B. jamaicensis* (red-tailed hawk)
  - *Buteo* sp. ? *B. lineatus* (red-shouldered hawk)
  - *Neophrontops vallecitoensis* ♦ † (Vallecito neophron)
- Family Falconidae
  - Genus and species indeterminate (kestrel, merlin or falcon)

Order Galliformes
- Family Phasianid
  - *Meleagris anza* ♦ † (Anza turkey)
  - Subfamily Odontophorinae
    - *Callipepla* sp. ? *C. californica* (California quail)
    - *Callipepla gambelii* (Gambel's quail)

Order Gruiformes
- Family Gruidae
  - *Grus canadensis* (sandhill crane)
- Family Rallidae
  - *Fulica americana* (American coot)
  - *F. hesterna* ♦ † (yesterday's coot)
  - *Gallinula* sp. (gallinules)
  - *Rallus* sp. (rails)
  - *Rallus limicola* (Virginia rail)

Order Charadriiformes
- Family Charadriidae
  - *Charadrius vociferus* (killdeer)

Order Strigiformes
- Family Strigidae
  - *Asio* sp. (eared owls)

Order Piciformes
- Family Picidae
  - Genus and species indeterminate (woodpeckers or wryneck)

Order Passeriformes
- Family Corvidae
  - *Corvus* sp. (crows)
- Family Fringillidae
  - Subfamily Carduelinae

Genus and species indeterminate (finches)
Family Emberizidae
Subfamily Embrizinae
Genus and species indeterminate (sparrows)

Class Mammalia (mammals)

Order Insectivora
Family Soricidae
Notiosorex jacksoni † (Jackson's desert shrew)
Sorex sp. (red-toothed shrews)
Family Talpidae
Scapanus malatinus † (mole)
Order Chiroptera
Family Vespertilionidae
Anzanycteris anzensis ♦ † (Anza-Borrego bat)
Myotis sp. (mouse-eared bats)
Order Xenarthra
Family Megalonychidae
Megalonyx jeffersoni † (Jefferson's ground sloth)
M. wheatleyi † (Wheatley's ground sloth)
Family Megatheriidae
Nothrotheriops sp. cf. *N. shastensis* † (Shasta ground sloth)
Family Mylodontidae
Paramylodon sp. ? *P. harlani* † (Harlan's ground sloth)
Order Lagomorpha
Family Leporidae
Subfamily Archaeolaginae
Hypolagus edensis † (Eden rabbit)
H. vetus H (ancient rabbit)
Pewelagus dawsonae ♦ † (Dawson's rabbit)
Subfamily Leporinae
Lepus sp. (jackrabbits)
? *Nekrolagus* sp. † (rabbits)
? Sylvilagus sp. (cottontail rabbits)
Sylvilagus hibbardi ♦ † (Hibbard's cottontail)
Order Rodentia
Family Sciuridae
Ammospermophilus leucurus (white-tailed antelope squirrel)
Eutamias sp. (chipmunks)
Spermophilus sp. (ground squirrels)
Family Geomyidae
Geomys anzensis ♦ † (Anza pocket gopher)
G. garbanii H (Garbani's pocket gopher)
Thomomys sp. (smooth-toothed pocket gopher)
Family Heteromyidae
Dipodomys sp. (A) † (kangaroo rat)
Dipodomys sp. (B) † (kangaroo rat)
Dipodomys sp. cf. *D. minor* † (small kangaroo rat)
D. compactus (gulf coast kangaroo rat)
D. hibbardi † (Hibbard's kangaroo rat)
Microdipodops sp. † (kangaroo mice)
Perognathus nr. *P. hispidus* (hispid pocket mouse)
Prodipodomys sp. † (extinct kangaroo rats)
Family Castoridae
Castor sp. (beaver)
Family Cricetidae
Baiomys sp. (pygmy mice)
Calomys (*Bensonomys*) sp. † (extinct mice)
Cosomys sp. † (Coso vole)
Lasiopodomys sp. cf. *L. deceitensis* † (Cape Deceit vole)

Microtus sp. ? *M. californicus* (California meadow vole)
Mictomys anzaensis ♦ † (Anza bog lemming)
Mimomys sp. cf. *M. parvus* † (small Snake River vole)
? *Nelsonia* sp. † (pygmy woodrats)
Neotoma (*Hodomys*) sp. (A) † (woodrat)
Neotoma (*Hodomys*) sp. (B) † (woodrat)
? *Ondatra idahoensis* † (Idaho muskrat)
Onychomys sp. (grasshopper mice)
Peromyscus sp. (white-footed mice)
Pitymys meadensis † (Mead's vole)
Pliopotamys minor † (pygmy muskrat)
Reithrodontomys sp. (harvest mice)
Sigmodon curtisi † (Curtis cotton rat)
S. lindsayi ♦ † (Lindsay's cotton rat)
S. medius and/or *S. minor* † (intermediate and/or small cotton rat)

Family Erethizontidae

Coendou stirtoni ♦ † (Stirton's coendou)

Order Carnivora

Family Canidae

Borophagus diversidens † (bone-eating dog)
Canis dirus † (dire wolf)
C. edwardii or *C. priscolatrans* † (Edward's dog or wolf-coyote)
Canis latrans (coyote)
Urocyon sp. (gray foxes)
Vulpes sp. (foxes)

Family Ursidae

Arctodus sp. ? *A. simus* † (short-faced bear)
Tremarctos sp. cf. *T. floridanus* † (Florida cave bear)
Ursus sp. cf. *U. americanus* (American black bear)

Family Procyonidae

Bassaricus casei † (Case's ringtail)
Procyon lotor (raccoon)
Procyon sp. cf. *P. rexroadensis* † (Rexroad raccoon)

Family Mustelidae

Gulo sp. (wolverine)
cf. *Lutra canadensis* (river otter)
Mustela sp. cf. *M. frenata* (long-tailed weasel)
Martes sp. (martin or fisher)
Spilogale sp. cf. *S. putorius* (spotted skunk)
Taxidea taxus (badger)

Subfamily Grisoninae

Gen and species indeterminate (grison)
Trigonictis macrodon Ray † (extinct grison)

Family Felidae

Miracinonyx sp. cf. M. inexpectatus † (North American cheetah)
Felis (*Panthera*) sp. † (large cat)
Felis concolor (mountain lion)
F. rexroadensis † (Rexroad cat)
Lynx rufus (bob cat)
Homotherium sp. cf. *H. serum* † (scimitar cat)
Smilodon gracilis † (gracile sabertooth)
Genus and species indeterminate (medium-sized cat)

Order Proboscidea

Family Mammutidae

Mammut sp. ? *M. americanum* † (mastodon)

Family Gomphotheriidae

Stegomastodon sp. † (stegomastodont)

Family Elephantidae

Mammuthus meridionalis ✝ (southern mammoth)

M. columbi ✝ (columbian mammoth) (= *M. imperator* of some authors)

Order Perissodactyla

Family Equidae

cf. *Dinohippus* sp. ✝ (Pliocene horse)

Equus (? *Hemionus*) sp. (half-ass)

Equus (*Asinus* or *Hemionus*) sp. (ass or half-ass)

Equus bautistensis ✝ (Bautista horse)

E. conversidens ✝ (Mexican horse)

E. (*Dolichohippus*) *enormis* ♦ ✝ (giant zebra)

E. (*Dolichohippus*) sp. cf. *E.* (*D.*) *simplicidens* ✝ (American zebra)

Equus (*Equus*) sp. A ✝ (medium-sized horse)

Equus (*Equus*) sp. B ✝ (medium-sized horse)

Equus sp. ? *E. pacificus* ✝ (Pacific horse)

Hippidion sp. ✝ (South American equid)

Family Tapiridae

Tapirus merriami ✝ (Merriam's tapir)

Order Artiodactyla

Family Tayassuidae

Platygonus spp. ✝ (peccaries)

Family Camelidae

Blancocamelus sp. ✝ (Blanco camel)

Camelops hesternus ✝ (yesterday's camel)

Camelops sp. aff. *C. huerfanensis* ✝ (Huerfano camel)

Hemiauchenia sp. ✝ (llama)

Hemiauchenia sp. ? *H. blancoensis* ✝ (Blanco llama)

Hemiauchenia sp. cf. *H. macrocephala* ✝ (large-headed llama)

Megatylopus sp. ✝ (large camel)

Titanotylopus sp. ✝ (giant camel)

Paleolama sp. ✝ (fossil llama)

Family Cervidae

Cervus sp. (elks)

Odocoileus cascensis ✝ (Casco deer)

Odocoileus sp. cf. *O. virginianus* (white-tailed deer)

cf. *Navahoceros* sp. ✝ (mountain deer)

Family Antilocapridae

Antilocapra sp. (pronghorn)

Capromeryx sp. ✝ (diminutive pronghorn)

Tetrameryx sp. ✝ (four-horned pronghorn)

Family Bovidae

? *Euceratherium* sp. ✝ (shrub-oxen)

Vertebrate Ichnites (tracks)

Division Vertebratichnia
Subdivision Avipedia (birds)

Order Charadriiformepeda

Family Avipedea

Avipeda sp. cf. *Calidris* sp. (sanderling track)

Avipeda sp. cf. *Tringa* sp. (sandpiper track)

Subdivision Mammalipedia (mammals)

Order Lagomorphipeda

Family Archaeolagipedidae

Archaeolagipeda sp. cf. *Hypolagus* sp. ✝ (rabbit track)

Order Carnivoripeda
Family Carvivoripedae
Subfamily Canipedinae
Canipeda sp. cf. *Borophagus* sp. † (bone-eating dog track)
Canipeda sp. cf. *Canis latrans* (coyote track)
Subfamily Felipedinae
Felipeda sp. cf. *Felis* sp. (cat track)
Felipeda sp. ? *Smilodon* sp. † (sabertooth track)
Order Proboscidipedida
Family Proboscipedidae
Proboscipeda sp. cf. Gomphotheriidae † (gomphothere or mastodon track)
Proboscipeda sp. cf. *Mammuthus* sp. † (mammoth track)
Order Perissodactipedida
Family Hippipedidae
Hippipeda sp. cf. *Dinohippus* sp. † (Pliocene horse track)
Order Artiodactipedida
Family Pecoripedidae
Pecoripeda sp. cf. *Blancocamelus* sp. † (Blanco camel track)
Pecoripeda sp. cf. *Camelops* sp. † (camel track)
Pecoripeda sp. cf. *Hemiauchenia* sp. † (llama track)
Pecoripeda sp. cf. *Megatylopus* sp. † (large camel track)
Pecoripeda sp. cf. *Titanotylopus* sp. † (giant camel track)

The materials collected by Hazen *et al.* are presently housed in the AMNH. Accessory data for most of these localities and specimens are archived also at the DSRC. The IVCM collection of fossil vertebrates was recovered from the BSF, CC and VCFC under a series of standard State permits (1970-1990). Over 7,000 specimens were collected and catalogued. Essentially the entire LACM collection of fossil vertebrates was recovered under State permits (1954-1985). Between 1954 and 1982, LACM staff and research associates recovered approximately 10,000 vertebrate specimens, primarily from the VCFC. Primary taxonomic holotypes have been retained by LACM, and are conserved within the Vertebrate Paleontology Section of that institution. In addition, the LACM presently houses California Institute of Technology specimens that were collected in the 1930's. A few vertebrate fossil specimens from the BSF are conserved by the Earth Sciences Section at the San Bernardino County Museum, Redlands.

MANAGEMENT ISSUES AND PRACTICES

Large parts of ABDSP have not been explored or surveyed for paleontologic remains (Jefferson 1999b). Many of these areas are remote, and human disturbance is presumed to be minimal. Nevertheless, paleontologic resources are also subject to rapid degradation through natural weathering processes. The significance of paleontologic resources, if any, in these unexplored territories will be assessed, and appropriate management plans formulated. Since 1993, the PS and CDD staff have been systematically intensively surveying (National Park Service 1977; Wylie 1991) specific areas within ABDSP, and significant fossil remains have been recovered. Baseline GIS locality data about the distribution and concentration of these resources is used to direct subsequent field operations and to plan cyclic surveys (Fremd 1995). Also, the condition of major vertebrate ichnite exposures is now annually photo-monitored and assessed.

The significance of paleontologic specimens must be evaluated in order to make proper decisions and take appropriate management actions (Fig 1). Fossils may have interpretive, historical, and/or scientific significance. While the former are relatively easy to determine, scientific significance may not be readily evident. For the purposes of intensive or cyclic paleontologic surveys at ABDSP, all vertebrate fossils taxonomically identifiable to the generic and in some cases to the Family or Ordinal level are considered scientifically significant. Hopefully, recovery of these specimens will allow future researchers to address biological guild level paleoecological issues.

However, no single criterion determines scientific significance, and some fossils may not be significant. Among the factors which make some specimens important are: represents poorly known taxa, preserves soft tissues or delicate structures, exhibits pathologies or injuries, unusual size or shape, reveals paleoecological relationships (such as symbiosis, parasitism, commensalism, predation), and/or are associated with datable stratigraphic horizons. However, many other subtle factors may make a specimen scientifically significant. Species that are abundantly represented may yield population-based data such as the degree of individual variation or sexual dimorphism (Remeika 1992a). Common taxa may record important geological and geographical range extensions, may be useful for regional geologic correlations, or provide information about depositional environments.

Management and protection of regionally distributed resources may require multi-agency cooperation. Recently, ABDSP and the BLM established an interagency agreement for the cooperative management of exposures of the IF in the CM area and Alverson Canyon, along the southern border of the Carrizo Impact Area of ABDSP (Remeika 1995). Here, the BLM lands have been designated an *Area of Critical Environmental Concern* because of the fossiliferous IF deposits.

As recreational land uses intensify, protection of paleontological resources from human actions, deliberate or unintentional becomes critical. Fortunately within ABDSP, poaching of specimens and vandalism of geological features has been minor. However, illegal trespass and damage by off-highway vehicular traffic has increased. Violations result in imprisonment and/or fines (punishment depends on the severity of the offence). Protective measures include route designations and access closures, signage and regular aerial and ground-based ranger patrols of sensitive areas. Rangers are made aware of the importance of resource protection and are provided with GIS generated maps for a variety of resources including fossils. Proactive measures include interpretive exhibits at the VC, park-wide AM radio information, public education pamphlets about fossils, and on site interpretive signage.

Fossils are a nonrenewable natural resource. If an organism has a fossil record, it is represented by a finite number of specimens, and that number decreases as fossils are destroyed by natural or human actions. Delimiting the geologic and geographic distribution of fossiliferous deposits, identification of the fossil materials, and evaluation of the significance of these paleontological resources are prerequisites to conscientious and responsible resource management. Promoting an understanding of these resources and their contribution to the biological prehistory of the California landscape is important to their protection and appreciation.

REFERENCES

A relatively complete bibliography on Salton Trough regional geologic and paleontologic topics has been complied by Jefferson *et al.* (1995). The abridged version below includes all citations that appear in this text and it has been updated with post-1995 publications.

Allen, C.R., 1954. Geology of the north side of San Gorgonio Pass, Riverside County. In Geology of Southern California, edited by R.H. Jahns, California Division of Mines Bulletin 170:map sheet 20.

Arnold, R.E., 1904. The faunal relations of the Carrizo Creek beds of California. Science 19:1-503.

—— 1906. The Tertiary and Quaternary pectens of California. U.S. Geological Survey Professional Paper 47:84-85.

—— 1909. Environment of the Tertiary faunas of the Pacific Coast of the United States. Journal of Geology 17:509-533.

Ballard, A., 1971. The paleoecology of a marine deposit in the northwest Indio Hills. Manuscript on File Department of Geological Sciences, University of California, Riverside 12 p.

Bauersfeld, A.G., 1971. Paleoecology of the Tertiary fauna, Willis Palms Formation, Thousand Palms quadrangle, California. Manuscript on File Department of Geological Sciences, University of California, Riverside 19 p.

Becker, J.J., and J.A. White, 1981. Late Cenozoic geomyids (Mammalia: Rodentia) from the Anza-Borrego Desert, southern California. Journal of Vertebrate Paleontology 1:211-218.

Bell, P.J., 1980. Environments of deposition, Pliocene Imperial Formation, southern Coyote Mountains, Imperial County, California. Master of Science Thesis, San Diego State University, California 72 p.

Bell-Countryman, P.J., 1984. Environments of deposition, Pliocene Imperial Formation, Coyote Mountains, southwest Salton Trough. In The Imperial Basin, Tectonics, Sedimentation and Thermal Aspects, edited by C.A. Rigsby, Society of Economic Paleontologists and Mineralogists 40:45-70.

Blackford, L.C., 1995. Postcranial skeletal analysis of the Pleistocene deer, *Navahoceros fricki* (Cervidae). Master of Science Thesis, Quaternary Studies, Northern Arizona University, Flagstaff 144p.

Bowers, S., 1901. Reconnaissance of the Colorado Desert Mining District. California State Mining Bureau 11:1-17.

Bramkamp, R.A., 1935. Stratigraphy and molluscan fauna of the Imperial Formation of San Gorgonio Pass, California. Doctoral Dissertation, University of California, Berkeley 371 p.

Brattstrom, B.H., 1961. Some new fossil tortoises from western North America with remarks on the zoogeography and paleoecology of tortoises. Journal of Paleontology 35(3):543-560.

California State Parks, 1998. Museum collections management handbook, volume I: basic references. Document on File, Museum Services Section, Park Services Division, Sacramento.

—— 2000. Museum collections management handbook, volume II: practices and procedures. Document on File, Museum Services Section, Park Services Division, Sacramento.

Campbell, K.E., E. Scott, Jr., and K.B. Springer, 1999. A new genus for the incredible teratorn (Aves: Teratornithidae). In Avian Paleontology at the Close of the 20th Century: Proceedings of the 4th International Meeting of the Society of Avian Paleontology and Evolution, Washington, D.C., edited by S.L. Olson, Smithsonian Contributions to Paleobiology 89:169-175.

Cassiliano, M.L., 1994. Paleoecology and taphonomy of vertebrate faunas from the Anza-Borrego Desert of California. Doctoral Dissertation, Department of Geosciences, University of Arizona, Tucson 421p.

—— 1997. Taphonomy of mammalian fossils across the Blancan-Irvingtonian boundary: Palm Spring Formation, Anza-Borrego desert of southern California. Palaeogeography, Palaeoclimatology, Palaeoecology 129:81-108.

—— 1998. Stable community structure of a terrestrial fauna in southern California across the Blancan-Irvingtonian boundary. Journal of Vertebrate Paleontology, Abstracts 18(3):32A.

—— 1999. Biostratigraphy of Blancan and Irvingtonian mammals in the Fish Creek section, southern California, and a review of the Blancan-Irvingtonian boundary. Journal of Vertebrate Paleontology 19(1)169-186.

Christensen, A.W., 1957. Part of the geology of the Coyote Mountain area, Imperial County, California. Master of Science Thesis, Department of Geology, University of California Los Angeles 188 p.

Coble, B.A., 1978. Intertidal environment in the Imperial Formation of southern California. Undergraduate Research Reports, Department of Geology, San Diego State University, California 33:16.

Conrad, T.A., 1854. Descriptions of new fossil shells of the United States. Journal of the Academy of Natural Sciences Philadelphia Series 2, 2(4):299-300.

—— 1855. Report on the fossil shells collected by W.P. Blake, geologist to the expedition under the command of Lieutenant R.S. Williamson, United States Topographical Engineers, 1852. In W.P. Blake, Preliminary Geological Report, U.S. Pacific Railroad Exploration, U.S. 33rd Congress, 1st session, House Executive Document 129:5-21, appendix.

Crouch, R.W., and C.W. Poag, 1979. *Amphistegina gibbosa* d'Orbigny from the California borderlands, the Caribbean connection. Journal of Foraminiferal Research 9(2):85-105.

Cunningham, G.D., 1984. The Plio-Pleistocene Dipodomyinae and geology of the Palm Spring Formation, Anza-Borrego Desert, California. Master of Science, Department of Geology, Idaho State University, Pocatello 193 p.

Dean, M.A., 1988. Genesis, mineralogy and stratigraphy of the Neogene Fish Creek gypsum, southwestern Salton Trough, California. Master of Science Thesis, San Diego State University, California 150 p.

—— 1996. Neogene Fish Creek gypsum and associated stratigraphy and paleontology, southwestern Salton Trough, California. In Sturzstroms and Detachment Faults Anza-Borrego Desert State Park California, edited by P. Abbott and D. Seymour, South Coast Geological Society Annual Field Trip Guide Book Number 24:123-148.

Deméré, T.A., 1993. Fossil mammals from the Imperial Formation (upper Miocene/lower Pliocene, Coyote Mountains, Imperial County, California. In Ashes, faults and basins, edited by R.E. Reynolds and J. Reynolds, San Bernardino County Museum Association Special Publication MDQRC 93(1):82-85.

Dibblee, T., 1954. Geology of the Imperial Valley region. In Geology of Southern California, edited by R.H. Jahns, California Division of Mines Bulletin 170:22-23.

Dickerson, R.E., 1918. Mollusca of the Carrizo Creek beds and their Caribbean affinities. Geological Society of America Special Paper 29:148.

Dockum, M.S. and R.H. Miller, 1982. Ordovician conodonts from the greenschist facies carbonates, western Imperial County, California. Geological Society of America Abstracts with Programs 14:160-161.

Douglas, A., 1971. Cenozoic marine faunas of the Imperial Formation of Whitewater and Fossil Canyon. Senior Thesis, Department of Geological Sciences, University of California, Riverside 24 p.

Dowlen, R.J., 1969. The coral-barnacle fauna of the Imperial Formation in Imperial County, California. Undergraduate Research Reports, Department of Geology, San Diego State University, California 14:1-34.

Downs, T., 1957. Late Cenozoic vertebrates from the Imperial Valley region, California. Geological Society of America Bulletin 68(12,2):1822.

—— 1965. Pleistocene vertebrates of the Colorado Desert, California. International Association for Quaternary Research, VII International Congress General Session, Abstracts with Programs p. 107.

—— 1966. Southern California field trip, Anza-Borrego Desert and Barstow areas. Society of Vertebrate Paleontology Field Trip, Manuscript on File Anza-Borrego Desert State Park, California 12 p.

—— 1967. Airlift for fossils. Los Angeles County Museum of Natural History Alliance Quarterly 6(1):20-25.

Downs, T. and G.J. Miller, 1994. Late Cenozoic equids from Anza-Borrego Desert, California. Natural History Museum of Los Angeles County Contributions in Science 440:1-90.

Downs, T., and J.A. White, 1965a. Late Cenozoic vertebrates of the Anza-Borrego Desert area, southern California. American Association for the Advancement of Science Meeting 1965:10-11.

—— 1965b. Pleistocene vertebrates of the Colorado Desert, California. International Association for Quaternary Research, VII International Congress, General Session Program p. 107.

—— 1966. The vertebrate faunal sequence of the Vallecito-Fish Creek area western Colorado Desert. In Southern California field trip, Anza-Borrego Desert and Barstow areas. Society of Vertebrate Paleontology Field Trip, Manuscript on File Anza-Borrego Desert State Park, California 5 p.

—— 1968. A vertebrate faunal succession in superposed sediments from late Pliocene to middle Pleistocene in California. In Tertiary/Quaternary Boundary, International Geological Congress 23, Prague 10:41-47.

Downs, T. and G.D. Woodard, 1961. Stratigraphic succession of the western Colorado Desert, San Diego and Imperial Counties, California. Geological Society of America Special Paper 68:73-74.

Durham, J.W., 1944. Lower California-Colorado Desert Area. In Correlation of the marine Cenozoic formations of western North America, chaired by C.E. Weaver, Bulletin of the Geological Society of America 55:574-575.

—— 1954. The marine Cenozoic of southern California. California Division of Mines Bulletin 170:23-31.

Durham, J.W. and E.C. Allison, 1961. Stratigraphic position of the Fish Creek gypsum at Split Mountain Gorge, Imperial County, California. Geological Society of America Special Paper 68:32.

FAIRBANKS, 1893. Geology of San Diego County, also portions of Orange and San Bernardino Counties. California State Mineral Bureau, 11th Annual Report of the State Mineralogist p. 88-90.

FLEMING, R.F., 1993a. Palynological data from the Imperial and Palm Spring Formations, Anza-Borrego Desert State Park, California. U.S. Geological Survey Open-File Report 93-678:1-29.

—— 1993b. Cretaceous pollen and Pliocene climate. The American Association of Stratigraphic Palynologists, Program and Abstracts, Annual Meeting 26: 24.

—— 1994a. Cretaceous pollen in Pliocene rocks: implications for Pliocene climate in the southwestern United States. Geology 22:787-790.

FLEMING, R.F., and P. REMEIKA, 1994. Pliocene climate of the Colorado Plateau and age of the Grand Canyon: evidence from Anza-Borrego Desert State Park, California. 4th NPS Conference on Fossil Resources, Colorado Springs, Colorado.

FOSTER, A.B., 1979. Environmental variation in a fossil scleractinian coral. Lethaia 12:245-264.

FREMD, T., 1995. Cyclic prospecting to preserve vertebrate paleontological resources. San Bernardino County Museum Quarterly 42(3):19-26.

FRICK, C., 1921. Extinct vertebrate faunas of the badlands of Bautista Creek and San Timoteo Canyon, southern California. University of California Publications, Department of Geological Sciences Bulletin 12:277-409.

GRANT, U.S., IV, and H.R. GALE, 1931. Pliocene and Pleistocene mollusca of California and adjacent regions. San Diego Society of Natural History Memoirs 1:1-1036.

Grant, U.S., IV, and L.G. Hertlein 1956. *Schizaster morlini*, a new species of echinoid from the Pliocene Imperial County, California. Southern California Academy of Sciences Bulletin 55:107-110.

HANNA, G.D., 1926. Paleontology of Coyote Mountain, Imperial County, California. Proceeding of the California Academy of Sciences, 4th Series, 14:427-503.

HERTLEIN, L.G. and E.K. JORDAN, 1927. Paleontology of the Miocene of lower California. Proceedings of the California Academy of Sciences, 4th Series 16(19):607-611.

HOWARD, H., 1963. Fossil birds from the Anza-Borrego Desert. Los Angeles County Museum Contributions in Science 73:1-33.

—— 1972a. Type specimens of avian fossils in the collections of the Natural History Museum of Los Angeles County. Natural History Museum of Los Angeles County Contributions in Science 228:1-27.

——— 1972b. The incredible teratorn again. Condor 74(3):341-344.

HUTCHISON, J.H., 1987. Moles of the *Scapanus latimanus* group (Talpidae, Insectivora) from the Pliocene and Pleistocene of California. Natural History Museum of Los Angeles County Contributions in Science 386:1-15.

INGLE, J.C. JR., 1974. Paleobathymetric history of Neogene marine sediments, northern Gulf of California. In Geology of Peninsular California, American Association of Petroleum Geologists, Society of Economic Paleontologists and Mineralogists, Society of Exploration Geophysicists Pacific Sections Fieldtrip Guidebook p. 121-138.

JASS, C.N., 1998. Preliminary report on two new localities from the Truckhaven region, Anza-Borrego Desert State Park, CA. Journal of Vertebrate Paleontology, Abstracts 18(3):53A-54A.

JEFFERSON, G.T., 1966. The paleoecology of a "borrow horizon" in the base of the Imperial Formation at Whitewater, California. Manuscript on File Department of Geological Sciences, University of California, Riverside 13 p.

—— 1989. Late Cenozoic tapirs (Mammalia: Perissodactyla) of western North America. Natural History Museum of Los Angeles County Contributions in Science 406:1-21.

—— 1994. Paleontology, a view of the past. In Anza-Borrego Desert State Park Newspaper, 1995 Edition, edited by J. Quirk, Anza-Borrego Desert Natural History Association and the California State Park System, Borrego Springs p. 3.

—— 1995a. Digging in the badlands, the camel excavation. Tracks, Colorado Desert District Newsletter, May, Borrego Springs, California p.1-3., and In Anza-Borrego Desert State Park Newspaper, 1995 Edition, edited by J. Quirk, Anza-Borrego Desert Natural History Association and the California State Park System, Borrego Springs p. 3.

—— 1995b. An additional avian specimen referrable to *Teratornis incrediblis* from the early Irvingtonian, Vallecito-Fish Creek Basin, Anza-Borrego Desert State Park, California. In Paleontology and geology of the western Salton Trough Detachment, Anza-Borrego Desert State Park, California, edited by P. Remeika and A. Sturz, Field Trip Guidebook and volume for the 1995 San Diego Association of Geologist's field trip to Anza-Borrego Desert State Park, Volume 1:94-96.

—— 1996b. Paleontologic resources and collections management policy, Colorado Desert District. Document on File, State of California, Department of Parks and Recreation, Natural Heritage Division, Sacramento, and Colorado Desert District Stout Research Center, Borrego Springs 35 p.

—— 1999a. A late Miocene terrestrial vertebrate assemblage from Anza-Borrego Desert State Park®. In The 1999 Desert Research Symposium, edited by R.E. Reynolds, Abstracts of Papers Submitted to the Meetings, San Bernardino County Museum Association Quarterly 46(3):109-111.

—— 1999b. Anza-Borrego Desert State Park® 622 Paleontologic Resources Inventory and Management Recommendations. Document on File, State of California, Department of Parks and Recreation, Colorado District Stout Research Center, Borrego Springs 36 p.

JEFFERSON, G.T., R. REMEIKA, and L.K. MURRAY, 1995. Selected bibliography of the western Salton Trough detachment and related subjects, Anza-Borrego Desert

State Park, California. In Paleontology and geology of the western Salton Trough Detachment, Anza-Borrego Desert State Park, California, edited by P. Remeika and A. Sturz, Field Trip Guidebook and volume for the 1995 San Diego Association of Geologist's field trip to Anza-Borrego Desert State Park, Volume II:1-88.

Jefferson, G.T. and A. Tejada-Flores, 1995. Late Blancan *Acinonyx* (Carnivora, Felidae) from the Vallecito Creek Local Fauna of Anza-Borrego Desert State Park, California. Abstracts of Proceedings. 9th Annual Mojave Desert Quaternary Research Symposium, San Bernardino County Museum Quarterly 42(2):33.

Johnson, N.M., N.D. Opdyke, G.D. Woodard, P.K. Zeitler, and E.H. Lindsay, 1983. Rates of Cenozoic tectonism in the Vallecito-Fish Creek basin. Geology 11:664-667.

Jolly, D.W., 2000. Fossil turtles and tortoises of Anza-Borrego Desert State Park®, California. Master of Science Thesis, Quaternary Studies, Northern Arizona University 196 p.

Keen, M. and H. Bentson, 1944. Check list of California Tertiary marine mollusca. Geological Society of American Special Paper 56:21-22.

Kerr, D.R. and P.L. Abbott, 1996. Miocene suberial sturzstrom deposits, Split Mountain, Anza-Borrego Desert State Park. In Sturzstroms and Detachment Faults Anza-Borrego Desert State Park California, edited by P. Abbott and D. Seymour, South Coast Geological Society Annual Field Trip Guide Book Number 24:149-163.

Kerr, D.R., S. Pappajohn, and G.L. Peterson, 1979. Neogene stratigraphic section at Split Mountain, eastern San Diego County, California. In Tectonics of the Juncture Between the San Andreas Fault System and the Salton Trough, Southeastern California, edited by J.C. Crowell and A.G. Sylvester, Geological Society of America Annual Meeting Guidebook p. 111-124.

Kew, W.S.W., 1914. Tertiary echnoids of the Carrizo Creek region in the Colorado Desert. California University Publications, Bulletin of the Department of Geology 8:39-60.

—— 1920. Cretaceous and Cenozoic echinoidea of the Pacific coast of North America. University of California Publication of the Geology Department 12(2):32-137.

Kidwell, S.M., 1988. Taphonomic comparison of passive and active continental margins: Neogene shell beds of the Atlantic coastal plain and northern Gulf of California. Palaeogeography, Palaeoclimatology, Palaeoecology 63:201-223.

Kidwell, S.M., C.D. Winker, and E. D. Gyllenhaal, 1988. Transgressive stratigraphy of a marine rift basin: Neogene Imperial Formation, northern Gulf of California. Geological Society of America Abstracts with Programs 20:A380.

Lasby, R.L., 1969. The stratigraphy and paleontology of the Imperial Formation at Cabazon, California. Senior Thesis, Department of Geological Sciences, University of California, Riverside 15 p.

Lindsay, E.H., N.M. Johnson, N.D. Opdyke, and R.F. Butler, 1987. Mammalian chronology and the magnetic time scale. In Cenozoic Mammals of North America, edited by M.O. Woodburne, University of California Press, Berkeley p. 212-235.

Lindsay et al., 1987. The North American Quaternary sequence. In Cenozoic Mammals of North America, Geochronology and Biostratigraphy, edited by M.O. Woodburne, University of California Press, Berkeley p. 269-290.

Lindsay, E.H. and J.S. White, 1993. Biostratigraphy and magnetostratigraphy in the southern Anza-Borrego area. In Ashes, Faults and Basins, edited by R. E. Reynolds and J. Reynolds, San Bernardino County Museum Association Special Publication 93-1:86-87.

Lundelius, E.L., Jr., T. Downs, E.H. Lindsay, H.A. Semken, R.J. Zakrzewski, C.S. Churcher, C.R. Harrington, G.E. Schultz, and S.D. Webb, 1987. The North American Quaternary sequence. In Cenozoic Mammals of North America, Geochronology and Biostratigraphy, edited by M.O. Woodburne, University of California Press, Berkeley p. 211-235.

Martin, R.A., 1993. Late Pliocene and Pleistocene cotton rats in the southwestern United States. In Ashes, faults and basins, edited by R.E. Reynolds and J. Reynolds, San Bernardino County Museum Association Special Publication 93(1):88-89.

Martin, R.A. and R.H. Prince, 1989. A new species of early Pleistocene cotton rat from the Anza-Borrego Desert of southern California. Southern California Academy of Sciences Bulletin 88(2):80-78.

McDaniel, G. and G.T. Jefferson, 1997. A Nearly Complete Skeleton of *Mammuthus meridionalis* from the Borrego Badlands, Anza-Borrego Desert State Park, California. In Memories, Minerals, Fossils, and Dust, edited by R.E. Reynolds and J. Reynolds, San Bernardino County Museum Association Quarterly 44(2):35-36.

—— 1999a. Distribution of proboscideans in Anza-Borrego Desert State Park®. In The 1999 Desert Research Symposium, edited by R.E. Reynolds, Abstracts of Papers Submitted to the Meetings, San Bernardino County Museum Association Quarterly 46(3):61-62.

——1999b. *Mammuthus meridionalis* (Proboscidea: Elephantidae) from the Borrego Badlands of Anza-Borrego Desert State Park®, California: phylogenetic and biochronologic implications. 2nd International Mammoth Conference, Rotterdam the Neatherlands, Abstracts p. 41-42.

——2001 (in press). *Mammuthus meridionalis* (Proboscidea: Elephantidae) from the Borrego Badlands of Anza-Borrego Desert State Park7, California: phylogenetic and biochronologic implications. 2nd International Mammoth Conference, Rotterdam the Netherlands, DEINSEA.

McDonald, H.G., G.T. Jefferson, and C. Force, 1996. Pleistocene distribution of the ground sloth *Nothrotheriops shastense* (Xenarthra, Megalonychidae). The 1996 Desert Research Symposium, Abstracts of Papers Submitted to the Meetings, San Bernardino County Museum Association Quarterly 43(1,2):151-152.

McDougall, K., C.L. Powell, J.C. Matti, and R.Z. Poore, 1994. The Imperial Formation and the opening of the ancestral Gulf of California. Geological Society of America Abstracts with Programs 26(2):71.

Mendenhall, W.C., 1910. Notes on the geology of Carrizo Mountain, San Diego County, California. Journal of Geology 18(4):337-355.

Merriam, R.H., and O.L. Bandy, 1965. Source of upper Cenozoic sediments in the Colorado River delta region. Journal of Sedimentary Petrology 35:384-399.

Miller, G.J., 1977. A new cervid (Mammalia; Cervidae) from Anza-Borrego Desert, Imperial Valley, California. Manuscript on File, Colorado Desert District Stout Research Center, Anza-Borrego Desert State Park®, California 15 p.

—— 1980. A new subgenus and two new species of *Odocoileus* (Mammalia; Cervidae) with a study of variation in antlers. Manuscript on File, Colorado Desert District Stout Research Center, Anza-Borrego Desert State Park®, California 21 p.

—— 1985. A look into the past of the Anza-Borrego Desert. San Diego Natural History Museum Environment Southwest 510:12-17.

Miller, G.J., P. Remeika, J.D. Parks, B. Stout, and V.E. Waters, 1988. A preliminary report on half-a-million-year-old cutmarks on mammoth bones from the Anza-Borrego Desert Irvingtonian. Mojave Desert Quaternary Research Symposium, Abstracts of Proceedings, San Bernardino County Museum Association Quarterly 35(3-4):41.

—— 1989. A preliminary report on half-a-million-year-old cutmarks on mammoth bones from the Anza-Borrego Desert Irvingtonian. Symposium on the Value of the Desert, Anza-Borrego Desert Foundation, Borrego Springs, California, Abstracts p. 8.

—— 1991. A preliminary report on half-a-million year old cut marks on mammoth bones from the Anza-Borrego Desert Irvingtonian. Imperial Valley College Museum Society Occasional Paper 8:1-47.

Miller, G.J., B. Stout, and P. Remeika, 1982. Irvingtonian ichnites from the Anza-Borrego Desert, California. Society of Vertebrate Paleontology, Abstracts with Programs 42nd Annual Meeting, Mexico City.

Miller, R.H., and M.S. Dockum, 1983. Ordovician conodonts from metamorphosed carbonates of the Salton Trough, California. Geology 11:410-412.

Mitchell, E.D., Jr., 1961. A new walrus from the Imperial Pliocene of southern California: with notes on odobenid and otariid humeri. Los Angeles County Museum Contributions in Science 44:1-28.

Morgan, T.G., 1971. The paleoecology of the Willis Palms Formation oyster beds. Manuscript on File Department of Geological Sciences, University of California, Riverside 11 p.

Mount, J.D., 1974. Molluscan evidence for the age of the Imperial Formation, southern California. Southern California Academy of Sciences Abstracts with Programs p. 9.

—— 1988. Molluscan fauna of the Imperial Formation. In Geologic Field Guide to the Western Salton Basin Area, edited by S.M. Testa and K.E. Green, American Institute of Professional Geologists p. 23-24.

Mueller, R.F., and K.C. Condie, 1964. Stability relations of carbon mineral assemblages in the southern California batholith. Journal of Geology 72:400-411.

Murphy, M.A., 1986. The Imperial Formation at Painted Hill, near Whitewater, California. In Geology Around the Margins of the Eastern San Bernardino Mountains, edited by M.A. Kooser and R.E. Reynolds, Inland Geological Society Publications, Redlands, California 1:63-70.

Murray, L.K., 1996. Curation manual for Anza-Borrego Desert State Park® and Colorado Desert District paleontological collections. Document on File, State of California, Department of Parks and Recreation, Colorado Desert District Stout Research Center, Borrego Springs 54 p.

Murray, L.K. and G.T. Jefferson, 1996. A review of the Procyonids (Carnivora) from the late Blancan and early Irvingtonian Vallecito Creek Local Fauna of Anza-Borrego Desert State Park, California. Abstracts of Proceedings, 10th Annual Mojave Desert Quaternary Research Symposium, San Bernardino County Museum Association Quarterly 43(1,2):153.

National Park Service, 1977. Paleontological resources management. Natural Resources Management Guideline, National Park Service NPS-77(2):155-175.

Norell, M.A., 1989. Late Cenozoic lizards of the Anza-Borrego Desert, California. Natural History Museum of Los Angeles County Contributions in Science 414:1-31.

Opdyke, N.D., E.H. Lindsay, N.M. Johnson, and T. Downs, 1974. The magnetic polarity stratigraphy of the mammal bearing sedimentary sequence at Anza-Borrego State Park, California. Geological Society of America Abstracts with Programs 6:901.

—— 1977. The paleomagnetism and magnetic polarity stratigraphy of the mammal-bearing section of Anza-Borrego State Park, California. Quaternary Research 7(3):316-329.

Pappajohn, S., 1980. Description of Neogene marine section at Split Mountain, easternmost San Diego County, California. Master of Science Thesis, San Diego State University 72 p.

Parks, J., B. Stout, G.J. Miller, P. Remeika, and V.E. Waters, 1989. A progress report on half-million year old marks on mammoth bones from the Anza-Borrego Desert Irvingtonian. Mojave Desert Quaternary Research Symposium, Abstracts of Proceedings, San Bernardino County Museum Association Quarterly 36(2):63.

Powell, C.L., II, 1984. Review of the marine Neogene Imperial Formation, southern California. Society of Economic Paleontologists and Mineralogists, Pacific Section p. 29.

—— 1986. Stratigraphy and bivalve molluscan paleontology of the Neogene Imperial Formation in Riverside County, California. Master of Science Thesis, California State University, San Jose 275 p.

—— 1987. Paleogeography of the Imperial Formation of southern California and its molluscan fauna: an overview. Western Society of Malacologists Annual Report 20:11-18.

—— 1995. Preliminary report on the Echinodermata of the Miocene and Pliocene Imperial Formation in southern California. In Paleontology and geology of the western Salton Trough Detachment, Anza-Borrego Desert State Park, California, edited by P. Remeika and A. Sturz, Field Trip Guidebook and Volume for the 1995 San Diego Association of Geologist's Field Trip to Anza-Borrego Desert State Park, Volume 1:55-63.

Quinn, H.A., and T.M. Cronin, 1984. Micro-paleontology and depositional environments of the Imperial and Palm Spring Formations, Imperial Valley, California. In The Imperial Basin, Tectonics, Sedimentation and Thermal Aspects, edited by C.A. Rigsby, Society of Economic Paleontologists and Mineralogists 40:71-85.

Remeika, P., 1988. Lower Pliocene petrified wood from the Palm Spring Formation, Anza-Borrego Desert State Park, California. Review of Palaeobotany and Palynology 56:183-198.

—— 1991. Formational status of the Diablo Redbeds; differentiation between Colorado River affinities and the Palm Spring Formation. Symposium on the Scientific Value of the Desert, Anza-Borrego Foundation, Borrego Springs, California, Abstracts p. 12.

—— 1992a. Anza-Borrego Desert State Park Paleontology Collection Management Policy. California Department of Parks and Recreation, Anza-Borrego Desert State Park 47 p.

—— 1992b. Preliminary report on the stratigraphy and vertebrate fauna of the middle Pleistocene Ocotillo formation, Borrego Badlands, Anza-Borrego Desert State Park, California. Mojave Desert Quaternary Research Symposium, Abstracts of Proceedings, San Bernardino County Museum Association Quarterly 39(2):25-26.

—— 1994. Lower Pliocene angiosperm hardwoods from the Vallecito-Fish Creek Basin, Anza-Borrego Desert State Park, California: deltaic stratigraphy, paleoclimate, paleoenvironment, and phytogeographic significance. Abstracts of Proceedings. 8th Annual Mojave Desert Quaternary Research Center Symposium. San Bernardino County Museum Association Quarterly 41(3):26-27.

—— 1995. Basin tectonics, stratigraphy, and depositional environments of the western Salton Trough detachment: the 1995 San Diego Association of Geologist's Field Trip Guide to Anza-Borrego Desert State Park, California. In Paleontology and geology of the western Salton Trough Detachment, Anza-Borrego Desert State Park, California, edited by P. Remeika and A. Sturz, Field Trip Guidebook and volume for the 1995 San Diego Association of Geologist's field trip to Anza-Borrego Desert State Park, Volume 1:3-54.

—— 1997a. Neogene Vallecito-Fish Creek Basin: tilt-block/half graben extension, stratigraphy, and paleontology. In Geology and Paleontology of the Anza-Borrego Region, California, edited by P. Dean, C. Metzler, and A. Trujillo, National Association of Geology Teachers, Far Western Section, Spring Conference Field Guide, Field Trip I 32 p.

—— 1997b. Roadside basin-margin outcrop geology of the Borrego Badlands: an overview. In Geology and Paleontology of the AnzaBorrego Region, Califonia, edited by P. Dean, C. Metzler, and A. Trujillo, National Association of Geology Teachers, Far Western Section, Spring Conference Field Guide, Field Trip IV 20 p.

—— 1998a. Interdisciplinary age control of the western Borrego Badlands, Anza-Borrego Desert State Park, California. National Park Service, Abstracts for the Fifth Fossil Conference, Rapid City, South Dakota, p.18.

—— 1998b. Marine invertebrate paleontology and stratigraphy of the Vallecito-Fish Creek Basin: a historic review, synthesis, and revision. In Geology and Hydrothermal Resources of the Imperial and Mexicali Valleys, edited by L. Lindsay and W.G. Hample, San Diego Association of Geologists Annual Field Trip Guidebook 1998 pp. 59-92.

Remeika, P., and S. Beske-Dehl, 1996. Magnetostratigraphy of the western Borrego Badlands, Anza-Borrego Desert State Park, California: implications for stratigraphic age control. In Geology of Neogene Faulting and Catastrophic Events in the Split Mountain Area, Anza-Borrego Desert State Park, California, edited by D. Seymour and P.L. Abbott, South Coast Geological Society Field Trip Guidebook 24:209-220.

Remeika, P., I.W. Fischbein, and S.A. Fischbein, 1986. Lower Pliocene petrified wood from the Palm Spring Formation, Anza-Borrego Desert State Park, California. In Geology of the Imperial Valley, California, edited by P.D. Guptil, E.M. Gath, and R.W. Ruff, South Coast Geological Society, Annual Field Trip Guidebook, Santa Ana, California 14:65-83.

Remeika, P., and R.F. Fleming, 1994. Pliocene climate of the Colorado Plateau and age of the Grand Canyon: evidence from Anza-Borrego Desert State Park, California. In Partners in Paleontology - - Proceedings of the Fourth Conference on Fossil Resources, edited by M. Johnson and J. McChristal, U.S. Department of the Interior Natural Resources Report NPS/NRFLFO/NRR-97/01 p. 17.

—— 1995. Cretaceous palynoflora and Neogene angiosperm woods from Anza-Borrego Desert State Park, California: implications for Pliocene climate of the Colorado Plateau and age of the Grand Canyon. In Paleontology and geology of the western Salton Trough Detachment, Anza-Borrego Desert State Park, California, edited by

P. Remeika and A. Sturz, Field Trip Guidebook and volume for the 1995 San Diego Association of Geologist's field trip to Anza-Borrego Desert State Park, Volume 1:64-81.

Remeika, P., and G.T. Jefferson, 1993. The Borrego Local Fauna: revised basin-margin stratigraphy and paleontology of the western Borrego Badlands, Anza-Borrego Desert State Park, California. In Ashes, Faults and Basins, edited by R.E. Reynolds and J. Reynolds. San Bernardino County Museum Association Special Publication 93(1):90-93.

Remeika, P., G.T. Jefferson, and L.K. Murray, 1995. Fossil vertebrate faunal list for the Vallecito-Fish Creek and Borrego-San Felipe Basins, Anza-Borrego Desert State Park and vicinity, California. In Paleontology and geology of the western Salton Trough Detachment, Anza-Borrego Desert State Park, California, edited by P. Remeika and A. Sturz, Field Trip Guidebook and volume for the 1995 San Diego Association of Geologist's field trip to Anza-Borrego Desert State Park, Volume 1:82-93.

Richardson, S.M., 1984. Stratigraphy and depositional environments of a marine-nonmarine Plio-Pleistocene sequence, western Salton Trough, California. Master of Science Thesis, San Diego State University, California 112 p.

Rymer, M.J., 1991. The Bishop ash bed in the Mecca Hills. In Geological excursions in southern California and Mexico, edited by M.J. Walawender and B.B. Hanan, Guidebook, 1991 Annual Meeting, Geological Society of America, San Diego State University, California p.388-396.

Schaeffer, G.C., 1857. Description of the structure of fossil wood from the Colorado Desert. In 1855 Report of the Explorations and Survey for a Railroad Route from the Mississippi to the Pacific, U.S. Congress, 2nd Session, Senate Executive Document 91, 5(2):338-339.

Schremp, L.A., 1981. Archaeogastropoda from the Pliocene Imperial Formation of California. Journal of Paleontology 55(5):1123-1136.

Stewart, J.D., and M. Roeder, 1993. Razorback sucker (*Xyrauchen*) fossils from the Anza-Borrego Desert and the ancestral Colorado River. In Ashes Faults and Basins, edited by R.E. Reynolds and J. Reynolds, San Bernardino County Museum Special Publication 93(1):94-96.

Stout, B.W., and P. Remeika, 1991. Status report on three major camel track sites in the lower Pliocene delta sequence, Vallecito-Fish Creek Basin, Anza-Borrego Desert State Park, California. Symposium on the Scientific Value of the Desert, Anza-Borrego Foundation, Borrego Springs, California p. 9.

Stump, T.E., 1970. Stratigraphy and paleoecology of the Imperial Formation in the western Colorado Desert. Undergraduate Research Reports, Department of Geology, San Diego State University, California 16(2):1-118.

—— 1972. Stratigraphy and paleoecology of the Imperial Formation in the western Colorado Desert. Master of Science Thesis, San Diego State University, California 128 pp.

Stump, T.E., and J.D. Stump, 1972. Age, stratigraphy, paleoecology and Caribbean affinities of the Imperial fauna of the Gulf of California depression. Geological Society of America Special Paper 4(3):243.

Taylor, D.W., 1966. Summary of North American Blancan nonmarine molluscs. Malacologica 4:1-172.

Tarbet, L.A., and W.H. Holman, 1944. Stratigraphy and micropaleontology of the west side of Imperial Valley. American Association of Petroleum Geologists Bulletin 28:1781-1782.

Thomas, H.W., and L.G. Barnes, 1993. Discoveries of fossil whales in the Imperial Formation, Riverside County, California: possible further evidence of the northern extent of the proto-Gulf of California. In Ashes, Faults and Basins, edited by R.E. Reynolds and J. Reynolds, San Bernardino County Museum Association Special Publication 93(1):34-36.

Tucker, A.B., R.M. Feldman, and C.L. Powell, II, 1994. *Speocarcinus berglundi* n. sp. (Decapoda: Brachyura), a new crab from the Imperial Formation (late Miocene-late Pliocene) of southern California. Journal of Paleontology 68(4):800-807.

Vaughan, T.W., 1904. A California Tertiary coral reef and its bearing on American Recent coral faunas. Science (new series) 19:503.

—— 1917a. The reef-coral fauna of Carrizo Creek, Imperial County, California and its significance. U.S. Geological Survey Professional Paper 98T:355-387.

—— 1917b. Significance of reef coral fauna at Carrizo Creek, Imperial Co., Calif. Washington Academy of Science Journal 7:194.

Watkins, R., 1990a. Pliocene channel deposits of oyster shells in the Salton Trough region, California. Palaeogeography, Palaeoclimatology, Palaeoecology 79:249-262.

—— 1990b. Paleoecology of a Pliocene rocky shoreline, Salton Trough region, California. Palaios 5:167-175.

Webb, S.D., 1998. Chronology and ecology of vertebrates: who went when. American Quaternary Association. Program and Abstracts of the 15th Biennial Meeting p. 66-68.

Webb, S.D. and A.D. Barnosky, 1989. Faunal dynamics of Pleistocene mammals. Annual Review of Earth and Planetary Sciences 17:413-438.

White, J.A., 1964. Kangaroo rats (Family Heteromyidae) of the Vallecito Creek Pleistocene of California. Geological Society of America Special Paper 82:288-289.

—— 1965. Late Cenozoic vertebrates of the Anza-Borrego Desert area, southern California. American Association for the Advancement of Science, Abstracts with Program, Berkeley, California.

—— 1968. A new porcupine from the middle Pleistocene of the Anza-Borrego Desert of California. Los Angeles County Museum of Natural History Contributions in Science 136:1-15.

—— 1969. Late Cenozoic bats (Subfamily Nyctophylinae) from the Anza-Borrego Desert of California. University of Kansas Museum of Natural History Miscellaneous Publications 51:275-282.

—— 1970. Late Cenozoic porcupines (Mammalia, Erethizontidae) of North America. American Museum Novitates 241:1-15.

—— 1984. Late Cenozoic Leporidae (Mammalia, Lagomorpha) from the Anza-Borrego Desert, southern California. Special Publication of the Carnegie Museum of Natural History 9:41-57.

—— 1991. North American Leporinae (Mammalia: Lagomorpha) from late Miocene (Clarendonian) to latest Pliocene (Blancan). Journal of Vertebrate Paleontology 11(1):67-89.

White, J.A. and T. Downs, 1961. A new *Geomys* from the Vallecito Creek Pleistocene of California. Los Angeles County Museum Contributions in Science 42:1-34.

—— 1965. Pleistocene vertebrates of the Colorado Desert, California. Abstract in Program, Association of Quaternary Research, VII International Congress, Denver, Colorado p. 107.

Wylie, J., 1991. The effects of wilderness designation on cultural resources. Manuscript on File, State of California, Department of Parks and Recreation, Colorado Desert District Stout Research Center, Borrego Springs 6 p.

Winker, C.D., 1987. Neogene stratigraphy of the Fish Creek-Vallecito section, southern California: implications for early history of the northern Gulf of California and Colorado delta. Doctoral Dissertation, University of Arizona, Tucson 494 p.

Winker, C.D. and S.M. Kidwell, 1996. Stratigraphy of a marine rift basin: Neogene of the western Salton Trough, California. In Field Conference Guide, edited by P.L. Abbott and J.D. Cooper, Pacific Section of American Association of Petroleum Geologists, GB 73, Pacific Section Society of Economic Paleontologists and Mineralogists, Book 80 p. 295-336.

Woodard, G.D., 1963. The Cenozoic succession of the west Colorado Desert, San Diego and Imperial Counties, southern California. Doctoral Dissertation, University of California, Berkeley 173 p.

—— 1974. Redefinition of Cenozoic stratigraphic column in Split Mountain Gorge, Imperial Valley, California. American Association of Petroleum Geologists Bulletin 58:521-539.

Woodring, W.P., 1931. A Miocene *Haliotis* from southern California. Journal of Paleontology 5:34-39.

Zakrzewski, R.J., 1972. Fossil microtines from late Cenozoic deposits in the Anza-Borrego Desert, California, with a description of a new subgenus of *Synaptomys*. Los Angeles County Museum of Natural History Contributions in Science 221:1-12.

THE FOSSIL RECORD AND CONTEMPORARY PROBLEMS IN ECOLOGY: CONTRIBUTIONS FROM SEMI-DEEP TIME

H. GREG McDONALD[1] AND DANIEL J. CHURE[2]
[1]Geologic Resources Division, National Park Service, P.O. Box 25287 Denver, CO, 80225
[2] Dinosaur National Monument, Jensen, UT 84035

ABSTRACT—The fossil record, particularly from the early Holocene and Pleistocene, can provide an historical basis for understanding long-term ecological change. Available data on the rate and types of environmental change in modern ecosystems is often limited to a few decades, whereas similar information provided by paleontological evidence can provide a record spanning thousands of years. This perspective becomes especially important in recognizing naturally occurring events that have a periodicity exceeding human observation. Thus the fossil record establishes a useful baseline for ascertaining whether changes impacting habitat have natural or anthropogenic causes. Fossil remains can also provide relaible documentation on the paleodistribution of endangered species and indicate areas favorable for reintroduction. Occasionally fossil preservation permits the recovery of DNA, allowing a very precise match between fossil and extant populations. More importantly, the paleoecological reconstruction of the former habitat has the potential for identifying new ranges where endangered species may be successfully introduced.

We do not advocate that the entire paleontological record will always be applicable to modern ecosystem management However, we do maintain that part of the record from "semi-deep time" extending tens to hundreds of thousands of years in the past is certainly relevant. Therefore, proper management of fossil resources is essential in preserving an irreplaceable record of environmental change. In turn, documentation of long term ecological history represents a potentially critical input in the decision-making process with regard to current ecological problems.

INTRODUCTION

"A science of land health needs, first of all, a base datum of normality, a picture of how healthy land maintains itself as a organism."
- Aldo Leopold (1941)

Paleontology as an historical science plays the key role in our understanding of the history of life on this planet, is it possible or even reasonable to think that this information can be used as a basis for decision-making in any contemporary environmental issues? The operative word is that paleontology is an historical science. As such, it can provide important background information on changes in the environment through time, and the subsequent response of plants and animals to environmental change, whether byadaptation, dispersal, local extirpation or extinction. It can therefore provide critical information and a historical perspective relevant to the management of modern ecosystems. It is in a very real sense necessary for establishing the "base datum of normality" identified by Leopold in the introductory quote. Certainly it can provide a foundation to distinguish processes and events that occur on a natural perhaps-cyclic basis and those that are anthropogenic. If management of natural processes is an objective, how do we identify changes that are the direct result of natural processes? The fossil record can provide a long-term view and in some cases direct documentation of changes that are an outcome of ongoing natural processes. This allows us to extract those that are the result of human activities.

Our purpose is to identify some sources of paleontological information that can aid managers of contemporary ecosystems. As an outgrowth of this main thesis, we believe that proper management of fossil resources on public lands is a critical component of a land managers obligations, not only because of their importance as part of a shared natural heritage, but because of the wealth of information from these resources related to modern ecosystems and their proper management.

DISCUSSION

Recognition of the potential contribution of paleontology to our understanding of the origin and history of modern ecological systems and long-term trends has been discussed by other workers, Archer et al. (1991), Graham (1992), Knudson (1999) and Swetham et al. (1999). Dayton et al. (1998) recognized that the detection of trends in ecosystems depends upon (1) a good description of the foundation or benchmark against which changes are measured and (2) a distinction between natural and anthropogenic changes. Although their study of a kelp forest was based on 25 years of direct observation, they recognized that this did not provide the needed time depth as many of the original species present in this ecosystem had disappeared before the study began. The fossil record can help distinguish between natural and anthropogenic changes to an environment by providing ecological and environmental information about an area prior to the appearance of humans. The source of information is not limited to the paleontological record and the archaeological record can also be used to provide continuity from the late Pleistocene and early Holocene to present (Lipe, 1995). Since the archeological record is the result of human activity allowances must be made for biases created by the human component.

Although each of the above authors has cited specific examples of paleontology's role in contemporary land management issues this paper's goal is to provide a broader overview of the information preserved in the fossil record that may be utilized to provide a historical perspective to contemporary management issues. The data obtainable from the fossil record will vary from region to region, and there is no "one size fits all" for what will be available. However, land managers, wildlife specialists and ecologists should be cognizant of the potential information in the fossil record in their area. This should foster an awreness they will better appreciate that management of fossil resources can contribute to their own expertise. This awareness should in turn result in the management of fossils resources being an essential element in any land management plan.

It is difficult to directly measure physical parameters of past climate, but fossil evidence may often serve as a useful proxy. The collection of multiple data sets such as pollen, insects, and mammals to support paleoclimatic interpretation is essential for a more accurate and refined understanding of past climate (Graham and Grimm, 1990). These indirect methods of inferring paleoclimatic parameters rely on modern analogs. This information can be complemented by analysis of stable isotopes preserved in plant and animal tissues. Studies of isotope ratios in unaltered biological materials can provide more direct evidence of past temperatures, humidity and rainfall. Typically carbon, oxygen, nitrogen, and hydrogen are utilized, but ongoing studies suggest that other stable isotopes, such as strontium may expand the types of data that can be extracted from the fossil record.

In some cases unaltered tissue can preserve the original DNA of plants and animals. Analysis of this DNA can complement traditional studies based on gross morphology to confirm the taxonomic identity of a particular species (see discussion below).

Information on past ecological conditions can come from a variety of data sources. In additional to bones, shells and macrobotanical remains, other sources in the fossil record that may be of interest to land managers include coprolites (fossil dung), packrat middens, and pollen. These can all provide different types of information, as will be discussed below.

FORMER DISTRIBUTION

At the simplest level the physical evidence from the skeleton of vertebrates, shells of invertebrates, macrobotanical specimens such as wood, leaves and flowers, and microfossils such as pollen can provide documentation for the presence of a taxon in the area. If the material can be dated by carbon 14 or some other method of absolute dating then the fourth dimension of time is added and provides the critical historical component. While a single record may be of interest to a specific place, such as evidence for the former presence of wolves in Yellowstone, examination of multiple records over a broad geographic area can provide important information such as shifts in distribution in horizontal directions and in elevation. The recovery of multiple taxa can indicate the previous association of species not found together today - a non-analog community that no longer exists as a result of changes in the environment.

The documentation of the former presence of a species in an area has its greatest relevance to species reintroduction. Rather than take the fossil evidence at face value, the question needs to be asked - if a species was once here why is it now gone? Is it merely a response to natural changes in the environment or the result of human activity? If the former, are present conditions sufficiently similar to permit a successful reintroduction or have the environmental parameters that permitted the species to previously live in the area changed to such a degree that its absence was a natural consequence of this change? With a sufficiently rich fossil record, spanning both time and geography, it is possible to trace changes in rates and patterns of a species' population and changes in its relative abundance. Has a particular species always been rare in the area, has its abundance decreased through time or is it a relative newcomer to the area? If a particular species is rare in an area does this mean it is a relict or represents the early stages of expansion of a species into the area? Houston and Schreiner (1995) posed the question, "given the dramatic changes in species distribution in North America from the close of the Pleistocene, what temporal and spatial scales of species distribution are appropriate to consider in defining 'alien' and 'natural' status in national parks?" "Is it appropriate for humans to introduce a species that has become extinct from natural causes into a park where the native fauna is to be retained intact?" As further noted by Houston and Schreiner (1995) "a policy without defined temporal and spatial bounds might lead to a 'whatever feels right' approach to the management of a particular species." Knowledge of the long-term history of a species based on the fossil record can provide those bounds. While the answer to these questions must be addressed on a case by case basis for each park, wilderness or natural area, ultimately part of the answer and decision-making process must rely on the fossil record. This data set should be local to establish the former presence of a species in the area, but should also examine the issue on a broader geographic scale, establishing within the limits of the fossil record, the former distribution of a species and how that distribution has changed through time. The analysis should consider the changes in environmental factors that have affected the species' distribution, and identify former ecological associates and conditions preserved in the fossil record that contributed to the distribution of the species.

Recently Cooper et al. (1996) performed a genetic study of bones of small ducks recovered from late Pleistocene and Holocene deposits on the chief Hawaiian Islands. Comparison of the DNA sequence of the fossil material with that of samples from living specimens of the endangered Laysan duck (currently known only from Laysan Island) showed that they were the same species. The fossil material had been recovered from sites in habitat varying from sea level to formerly forested areas at high elevations (60 – 1,800 m), far from permanent water on the Hawaiian Islands, demonstrating that this endangered species is not as restricted ecologically as its present distribution would suggest. Consequently the data has important implications for the recovery of this species and offers a wider range of options for reintroduction into its former range. As the authors point out, the utilization of DNA analysis to confirm the identity of a species that may not be possible based on gross morphology, can be applied to other threatened insular species as part of an integrated recovery plan.

An interesting collateral issue related to species reintroduction is the introduction of "exotic species". Proposals that exotic species be introduced into a region have centered on two lines of thought. Martin (1975) suggested that certain modern species could serve as ecological equivalents to now extinct Pleistocene species in an area. While viewed as exotic, it was argued that some modern species, such as the burro in the Grand Canyon, filled a now vacant ecological niche created by the disappearance of horses in North America at the end of the Pleistocene. Martin (1981) proposed three levels of faunal introduction in order to restore lost biodiversity in a habitat, based on taxonomic affinities. Mellink (1995) extended Martin's proposal a step further by suggesting exotic species introduced onto rangeland need not be taxonomically close to now extinct species, but only be ecologically similar in habits. The presence of open niches also requires an assessment of whether an exotic species utilizes previously unused resources and hence is not in competition with any native species. Mellink (1995) provided an outline for increased carrying capacity in a multispecies community composed of exotic species selected from a variety of sources. In engineering this complex and totally artificial mammalian community, the selection of species was partially based on body size along a gradient in order to minimize competition. Identification of optimum body sizes was in part based on examining the fossil record to determine the body size of extinct species that formerly lived in the area. Whether or not one agrees philosophically with the concept of "ecological engineering" as an approach to economic development of rural areas as proposed by Mellink, his proposal illustrates an intrigueing use of the fossil record.

TIMING AND FREQUENCY OF NATURAL DISTURBANCES

A basic ecological tenet is that communities are not static, but constantly changing. The concept of ecological succession in plant communities and associated fauna is well established. This type of ecological change is temporally restricted, and any disturbance has been viewed as a temporary resetting of the system, that will restart as soon as the disturbance is over. This view of ecological change has not taken into account long-term climatic change that may affect ecological succession. The fossil record can also document the frequency and intensity of ecological disturbances. One such disturbance that has received considerable attention is wildland fire. While ecological recovery from a fire may remove most of the evidence, there are often places, such as pond deposits and cave sediments, where fire history is preserved. Fire history for the Yellowstone region has been documented based on study of sediments in ponds (Millspaugh and Whitlock, 1995; Whitlock and Millspaugh, 1996; and Millspaugh, Whitlock, and Bartlein, 2000).

In their study of plant communities in the Appalachian Mountains, Delcourt and Delcourt (1998) noted that the current landscape was not stable and was composed of a fine-grained, heterogeneous mosaic of habitats resulting from increased seasonality of climate that occurred during the changeover from glacial to interglacial conditions in the late Pleistocene and Holocene. The overall effect produced a diverse biota often represented by localized disjunct populations of limited distribution. Such relict habitats, and their included species, both plant and animal, are particularly vulnerable to environmental change, either locally or globally. Based on their study of the response of various plant communities during the Pleistocene and shifts in the ecotones between alpine, boreal and temperate ecosystems, they project that continued warming due to increased levels of greenhouse gases would result in the loss of alpine tundra between 44º and 57º N and that the Picea rubens-Abies fraseri forests would become extinct in the southern Appalachians. The preservation of relict, often fragile, habitats tend to figure prominently in park management plans. If such habitats are within a land manager's jurisdiction and long-term management strategy includes the preservation of these relict biotas, then an understanding of the response of these biotas to climatic change through time may provide critical information related to that strategy. While the database utilized by the Delcourts covered a wide geographic region from Labrador in the north to Louisiana in the south, it was composed of numerous individual sites such as ponds that preserved pollen and other biological materials. Each of these sites played a dual role, providing both the local history of biotic change, and when combined with numerous other sites, generating a broader regional picture of climatic and biotic change. Preservation of the fossils that are source of this information resulted not only in the historical documentation of how these plant communities have responded to climatic change but also permitted the construction of a predictive model of how they would respond to future changes.

INDIVIDUAL SPECIES RESPONSE VS. COMMUNITIES

When did the modern range of a species become established or is it even possible to say that a species is in an established range? Many species are still dispersing into available habitat, thus making them an invader. One such example is the western larch, Larix occidentalis (Whitlock, 1995). Today the range of the western larch is restricted and discontinuous. This current distribution may indicate either a fragmentation of a once widespread distribution now limited due to unfavorable conditions, or alternatively is the result of dispersal with isolated stands indicating range expansion resulting from ameliorating conditions. This presents a manager with two diametrically opposed processes. Is a rare species a relict population that is on the decline or indicative of the early stages of the species reestablishing itself in former habitat? If considered to be an invading alien species the management approach will be different than if it is viewed as a recovering species in need of special attention. If the species is not an exotic introduced species and is spreading through natural processes, then it would not be considered an alien and management should remain neutral with regard to its management. If on the other hand its spread is the result of human activities then active involvement in its managmeent may be required. Resolution of this question may be dependent on the fossil record, both from the pollen record and macrobotanical remains, utilizing both local and regional data. The same approach can be applied to small mammals, insects and other parts of the biota as well.

Recognition of the dynamics of species through time and how they respond to climatic or environmental change may be critical in the design and space allocation for biological preserves. Studies of changes in the composition of mammalian communities during the Pleistocene has shown that each species reacts independently to changes in climatic parameters and that many past communities lack modern analogs (FAUNMAP, 1996). Dayton et al. (1998) in their study of kelp forest communities indicated that the community was not tightly integrated with mutual dependencies and that many species could be removed without much effect on the rest of the ecosystem. If this is the case, although we now have an extant species missing from a habitat when its former presence is indicated by the fossil record, then the question for a manager is whether that species should be reintroduced into that ecosystem. Adjustments to changes in various environmental parameters reflected in the range of small mammals continued through the Holocene (Semken, 1983). Hence the community structure present in a given area may be of relatively recent origin and indicate a single stage in a dynamic ongoing process. This individualistic response is also true of plant associations (Jackson and Overpeck, 2000) and results in non-analog floras.

Reconstruction of former plant communities can come from pollen preserved in the sediments in current or former lakes. In the arid southwest additional information has come from plants preserved in the middnes of packrats, Neotoma spp. in which organic material has been cemented and preserved by the urine of the animals. These middens increase in size due the collecting habits of packrats over many generations and can span thousands of years, thus providing a long-term record of vegetation change in the area. Packrat middens will also contain other organic material such as bones and insect remains (Betancourt et al., 1990; Clark and Sankey, 1999).

If the current philosophy of land managers is to preserve and protect natural ecological processes and not to establish a static assemblage of plants and animals based on an arbritary time standard (usually just before European appearance in a given area) then it is necessary to gain a long term perspective of those processes and their dynamics. We are not managing for ecological stasis. Our fixation on the impact by European settlers is unrealistic and ignores human influence on the environment prior to 1492 (Kay, 1994). As noted by Dayton et al. (1998) the lack of long–term historical data for most ecosystems forces ecologists to use sliding baselines in evaluating the degree of impact and amount of change occurring in an ecosystem. While there will never be a single baseline that is applicable to all situations, the fossil record, within the limits of what is preserved in a given area, can provide data not otherwise available and improve our knowledge of how “natural” a particular system may be.

In our attempts to distinguish natural processes vs. anthropogenic impact the usual reference point in time is pre- and post- appearance of Europeans. This is especially true with evaluation of the impact on an environment caused by the European introduction of domestic species that have since established feral populations. Although wild horses and donkeys have received a lot of attention as to whether they are merely filling empty niches left by the Pleistocene extinctions (Martin, 1975), there are other feral domesticates such as hogs in the eastern Unites States and goats on the Channel Islands of California that create management challenges. This is further complicated by popular species introduced for hunting such as pheasant and chukar partridges whose management may conflict with the protection of native species with less appeal such as foxes and coyotes. Even the reintroduction of native species into an area often results in controversy, such as mountain goat on the Olympic Peninsula. Both sides of the controversy have supported their claims for the eradication or preservation of the mountain goat utilizing knowledge from both the fossil and archeological records of the area. (Lyman, 1988). As is often the case in paleontology, the differences in opinion are due to the lack of direct evidence, in this case, of the former presence of mountain goats on the Olympic Peninsula. But does that argument have much merit? It can be argued that their absence in the area can be explained as nonpreservation in the fossil record rather than never having lived there. While the fossil record is silent on this particular issue, it does illustrate that one well preserved fossil locality containing mountain goat on the Olympic Peninsula could change the entire complexion of the argument regarding the Park Service’s plan for either removal or management. Foes of the eradication program seem to have the current advantage by arguing that the animal was present but the right fossil has just not yet been found. However, is this a valid use of the fossil record, to use absence of evidence to support an argument. Rather than this selective use of the fossil record the entire distribution of the fossil and modern record of the species needs to be examined. By looking at patterns of distribution and biogeographic barriers it then becomes possible to at least make a reasonable extrapolation as to the former presence of a species in a particular spot.

While there is a general recognition that the extinction of the Pleistocene megafauna must have had some impact on various ecosystems (Burkhardt, 1996) there has been little work done to determine the long-term impact resulting from their disappearance. Have the ecosystems rebounded, adapted, and returned to some type of equilibrium or are they still in flux? Recently Janzen and Martin (1982) pointed out that the structures of certain neotropical fruits suggest that they may have relied on being ingested by megaherbivores to facilitate propagation. Any plans by managers to maintain a tract of tropical forest with these plant species may need to provide alternative methods for the plants to propagate. Some type of artificial means of propagation may be required if the species involved are to maintain a reasonable level of recruitment of new individuals that would not otherwise occur naturally. This does pose the bigger question as to whether this is the appropriate management strategy. If these species of plants have co-evolved with now extinct species of mammals then perhaps the appropriate action is not to interfere but let the natural process of their eventual extinction occur.

While the above example is based on an inferred relationship between the plants and an extinct species, there are also sources of direct evidence for plant-animal interaction. Recently James and Burney (1997) analyzed the coprolites (fossil fecal matter) from five species of large flightless waterfowl from Hawaii. All species were primarily folivorous and ferns were an important part of their diet. A close coevolutionary relationship between some waterfowl and plants, such as the lobelia, Cyanea, was proposed. Among the conclusions drawn from their study is that the loss of avian herbivores may have affected the nature of selection that certain plants are exposed to and the nature of competition for light among plants on the forest floor. Both factors affect regeneration in certain species. Certainly such information needs to be taken into account as part of the management of these species.

Even the coprolites of an extinct species can provide important information on long-term changes in vegetation for an area. Rampart Cave in the Grand Canyon contains a large stratified layer of dung of the extinct ground sloth, Nothrotheriops shastensis. Analysis of the dung permitted the identification of plants growing in the vicinity of the cave over the last 40,000 years. While the animal producing the dung is now extinct many of the plant species found in the dung are still in the area. As a result of the animal's eclectic eating habits and the preservation of the dung we have gained a long-term perspective on the history of the ecosystem in this part of the Grand Canyon. This also presents the interesting paradox that many of the types of plants preserved in the dung are still found in the vicinity of the cave that preserved the dung, even though the animal that fed on the plants is extinct.

SUMMARY

Land managers, wildlife biologists, ecologists and all individuals interested in the conservation and long-term management of our living natural resources require the best possible information in order to make informed decisions. An often overlooked source of information is the fossil record which can provide critical historical information on ecological trends, community structure and history of individual species for an area. Often the source of this information is preserved in the same place as the contemporary ecological communities that they are responsible for managing. While current ecological problems, threatened and endangered species and human impact may seem consuming and of more immediate concern, land managers should be equally concerned with the protection and preservation of fossil resources as well. It may be that the information preserved in the fossil record when properly studied and deciphered can aid them in making those informed decisions that will ultimately affect the fate of the modern ecosystems they are charged with protecting and delay their entry into the fossil record.

REFERENCES

Archer, M., S.J. Hand, and H. Godthelp, 1991. Back to the future: the contribution of palaeontology to the conservation of Australian forest faunas. pp. 67-80 *in* D. Lunney (ed.). Conservation of Australia's Forest Fauna. Royal Zoological Society of New South Wales.

Archer, M., S.J. Hand, and H. Godthelp, 1999. The Power of Paleontology, a new tool for conservation. pp. 233-244 *in* Australia's Lost World, Prehistoric Animals of Riversleigh. Indiana University Press, Bloomington.

Betancourt, J.L., T.R. Van Devender, and P.S. Martin, 1990. Packrat middens: the last 40 000 years of biotic change. University of Arizona Press, Tucson, Arizona, USA.

Burkhardt, J.W., 1996. Herbivory in the Intermountain West. Idaho Forest, Wildlife and Range Experiment Station, Moscow, Idaho Station Bulletin 58:1-35.

Clark, W.H. and J.T. Sankey, 1999. Late Holocene Sonoran Desert arthropod remains from a packrat midden, Cataviña, Baja California Norte, México. Pan-Pacific Entomologist 75:183-199.

Cooper, A., J. Rhymer, H.F. James, S.L. Olson, C.E. McIntosh, M.D. Sorenson, and R.C. Fleischer, 1996. Ancient DNA and island endemics. Nature 381:484.

Dayton, P.K., M.J. Tegner, P.B. Edwards, and K.L. Riser, 1998. Sliding baselines, ghosts, and reduced expectations in kelp forest communities. Ecological Applications 8(2):309-322.

Delcourt, P.A. and H.R. Delcourt, 1998. Paleoecological insights on conservation of biodiversity: a focus on species, ecosystems, and landscapes. Ecological Applications 8(4):921-934.

FAUNMAP Working Group: R.W. Graham, E.L. Lundelius Jr., M.A. Graham, E.K. Schroeder, R.S. Toomey III, E.

ANDERSON, A.D. BARNOSKY, J.A. BURNS, C.S. CHURCHER, D.K. GRAYSON, R.D. GUTHRIE, C.R. HARINGTON, G.T. JEFFERSON, L.D. MARTIN, H.G. MCDONALD, R.E. MORLAN, H.A. SEMKEN JR., S.D. WEBB, L. WERDELIN, and M.C. WILSON, 1996. Spatial response of mammals to late Quaternary environmental fluctuations. Science 272(5268):1601-1606.

GRAHAM, R.W., 1992. Late Pleistocene faunal changes as a guide to understanding effects of greenhouse warming on the mammalian fauna of North America. pp. 76 – 87 *in* R.L. Peters and T.E. Lovejoy (eds.). Global Warming and Biological Diversity, Yale University Press, New Haven.

GRAHAM, R.W. and E.C. GRIMM, 1990. Effects of global climate change on the patterns of terrestrial biological communities. Trends in Ecology and Evolution 5(9):289-292.

HOUSTON, D.B. and E.G. SCHREINER, 1995. Alien species in National Parks: drawing lines in space and time. Conservation Biology 9(1):204-209.

JACKSON, S.T. and J.T. OVERPECK, 2000. Responses of plant populations and communities to environmental changes of the late Quaternary. pp. 194 –220 *in* D.H. Erwin and S.L. Wing (eds.) Deep Time. Paleobiology's Perspective. Paleobiology Supplement to Volume 26 (4).

JAMES, H.F. and D.A. BURNEY, 1997. The diet and ecology of Hawaii's extinct flightless waterfowl: evidence from coprolites. Biological Journal of the Linnean Society 62:279-297.

JANZEN, D.H. and P.S. MARTIN, 1982. Neotropical anachronisms: the fruits the gomphotheres ate. Science 215(4528);19-27.

KAY, C.E., 1994. Aboriginal overkill: the role of native Americans in structuring western ecosystems. Human Nature 5(4):359-398.

KNUDSON, R., 1999. Using the past to shape National Park Service policy for wildlife. The George Wright Forum 16(3):40-51.

LEOPOLD, A., 1941. Wilderness as a land laboratory. Living Wilderness 6:3.

LIPE, W.D., 1995. The archeology of ecology. Federal Archeology 8(1):8-13.

LUNNEY, D., B. PRESSEY, M. ARCHER, S. HAND, H. GODTHELP, and A. CURTIN, 1997. Integrating ecology and economics: illustrating the need to resolve the conflicts of space and time. Ecological Economics 23:135-143.

LYMAN, R.L., 1988. Significance for wildlife management of the late Quaternary biogeography of mountain goats (*Oreamnos americanus*) in the Pacific Northwest, USA. Arctic and Alpine Research 20:13-23.

MARTIN, P.S., 1975. Pleistocene niches for alien animals. Bioscience 20:218-221.

MARTIN, P.S., 1981. Beyond *Bos*: is nothing better? pp. 33-61 *in* C.E. Brock and J.H. Bock (eds.) Proceedings of Symposium on Southwestern Grasslands: Past, Present, and Future. Appleton-Whittell Research Ranch, Elsin, Arizona.

MELLINK, E., 1995. Use of Sonoran rangelands: lessons from the Pleistocene. pp. 50-60 *in* D.W. Steadman and J.I. Mead (eds.). Late Quaternary Environments and Deep History, a tribute to Paul S. Martin. The Mammoth Site of Hot Springs, South Dakota, Inc. Scientific Papers 3.

MILLSPAUGH, S.H. and C. WHITLOCK, 1995. A 750-year fire history based on lake sediment records in central Yellowstone National Park, USA. The Holocene 5(3):283-292.

MILLSPAUGH, S.H., C. WHITLOCK, and P.J. BARTLEIN, 2000. Variations in fire frequency and climate over the past 17000 yr in central Yellowstone National Park. Geology 28(3):211-214.

SEMKEN, H.A. JR., 1983. Holocene mammalian biogeography and climatic change in the eastern and central United States. pp. 182 –207 *in* H.E. Wright Jr. (ed.). Late Quaternary Environments of the United States. Vol. 2, The Holocene. University of Minnesota Press, Minneapolis.

SWETHAM, T.W., C.D. ALLEN, and J.L. BETANCOURT, 1999. Applied historical ecology: using the past to manage for the future. Ecological Applications 9(4):1189-1206.

WHITLOCK, C., 1995. The history of *Larix occidentalis* during the last 20,000 years of environmental change. pp. 83-90 *in* Ecology and Management of *Larix* Forests: A Look Ahead. W.C. Schmidt and K.J. McDonald (eds.). United States Forest Service, Intermountain Research Station General Technical Report GTR-INT-319.

WHITLOCK, C. and S.H. MILLSPAUGH, 1996. Testing the assumptions of fire-history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. The Holocene 6(1):7-15.

IMPLEMENTING THE PUBLIC TRUST IN PALEONTOLOGICAL RESOURCES

JOSEPH L. SAX
James H. House & Hiram H. Hurd Professor
Boalt Hall (Law School), University of California, Berkeley, CA 94720

Abstract—The historic public trust relating to navigable waters is not directly applicable to the federal public lands. But the broader public trust principle that knowledge is in the public domain provides an important rationale for protecting scientifically significant fossil resources. Since paleontological knowledge is embedded in material objects (fossils) and in information provided by their site, the trust principle denies any right to disturb, destroy, or possess fossils so as to impair their scientific significance. Laws that require permits for excavation; that impose restrictions on permits so as to protect and preserve knowledge and opportunities for scientific work; and that assure safeguarding of significant materials in appropriate repositories; are all appropriate to implement the public trust. In principle the trust applies to scientifically valuable fossil resources wherever they are found. The United States has thus far been slow to adopt some of the legislation necessary to implement public trust obligations in the field of paleontology, though a range of practical and known legislative techniques are available.

LEGAL STATUS OF THE PUBLIC TRUST CONCEPT AS APPLIED TO THE FEDERAL LANDS

The public trust as a legal concept exists in several dif ferent forms. In its most familiar setting it is a com mon law (judicially developed) concept drawn from Roman Law that recognizes a public right in navigable waters and the lands under them, and sometimes in the seashore. This doctrine has been widely adopted in the United States and is implemented independently by each State of the Union, and not as a matter of federal law. This judicially fashioned and implemented historical trust has never been understood to apply to the federal lands (1970; 1980).

Though it has not been authoritatively settled by the U.S. Supreme Court, the general understanding is that the United States–insofar as the federal lands are concerned–has only those obligations that it imposes upon itself by statute, or by regulation or policy pursuant to statutory authorization. Thus, Congress may (and sometimes does) determine that certain of its resources are held in public trust. It then constitutes the United States as a trustee of those resources and determines the scope and content of its trust obligation. It has recognized itself as a trustee in some statutes, sometimes explicitly, sometimes implicitly (that is, without using the term trust or public trust in so many words). The important point is that courts look to federal statutes and regulations, and not to common law principles, to determine the presence or absence of a trust obligation governing the federal lands, and to the scope of any such obligation.

There is no general statute governing protection of paleontological resources on the federal lands (1987;1994) as there is for archeological resources under the Archeological Resources Protection Act, known as ARPA (1979). ARPA expressly excludes paleontological remains from its coverage, except those associated with archeological sites. There are, however, some statutes that explicitly provide fossils protection in various specific settings (1975;1980a; 1988; 1994a). In addition, Congress has provided for fossil protection in various areas, such as the Florissant Fossil Beds National Monument in Colorado (1969), Fossil Butte National Monument in Wyoming (1972) and Agate Fossil Beds National Monument in Nebraska (1969a) by bringing those areas under the jurisdiction of the National Park Service and thereby (1970a) under the protection afforded by the National Park Service Organic Act, and the Regulations and Management Policies of the Park Service (1916; 2001; 2001a). Federal laws of broad application, such as the Federal Land Policy and Management Act (1976), which governs the public lands managed by the Bureau of Land Management, can provide implicit protection for fossils through provisions that call for the public lands to be managed in a manner that protects the quality of scientific, historical, archeological and other values . Statutes such as these authorize the promulgation of administrative directions providing detailed protection and management of fossil resources on public lands. Among the regulatory protections provided are provisions that collections shall be deposited in public museums and must be accessible to the public (2001b).

One may appropriately characterize the above-mentioned statutes and implementing regulations as recognition by the Congress and federal agencies of a federal "public trust" responsibility (1995). Indeed, the Secretary of the Interior in a report on fossil protection, explicitly spoke of "keeping these scientifically important specimens in the public trust." (2000).

One of the central elements of "public trust" as a legal concept is that government is not merely empowered to act to protect certain interests, but bears an obligation to protect interests that are fundamentally important to the nation. The most familiar setting in which governments acknowledge a trust responsibility is where national history is concerned.. It would be difficult to imagine a nation worthy of the name that did not consider itself obliged to protect the records of its founding (such as the Declaration of Independence), or to memorialize its great catalyzing events (such as the Revolutionary and Civil Wars). It is also conventional for nations to preserve and protect the symbols as well as the substance of its epochal achievements in art, literature, and science. In adopting official acts to memorialize these events and to recognize and perpetuate these achievements, government acts as a trustee. Nevertheless, for the most part, nothing compels government to take on the role of trustee. Its responsibility is ultimately to history (1986, 1991), and at times governments fail disastrously, as all the world witnessed in the wave of cultural vandalism that swept through Afghanistan in the first months of 2001 (2001c).

THE PUBLIC TRUST CONCEPT AS A GUIDELINE FOR PROTECTION OF PALEONTOLOGICAL RESOURCES ON THE PUBLIC LANDS

How does one identify those responsibilities that should engage the government's role as a public trustee? How should the trust concept apply to fossils on the federal public domain (and elsewhere)? Broadly stated, public trust describes those things that by their nature are understood to belong in the public domain as the common heritage of all, and as primary elements of a community's common history, experience and aspirations. Probably the single best known element of this heritage is knowledge: what we take from the past, share, build on, and pass forward through the generations. Knowledge, along with our genetic heritage, are our most fundamental common possessions.

The commitment of civilized communities to safeguarding their common heritage by investing relevant resources with a special public character is the essence of the public trust. It finds recognition in various settings in our legal system, as to knowledge, most notably in the theory underlying the limitations on proprietary rights in our laws governing matters such as patent and copyright. No one can patent (that is, privatize, even for a limited time) the theory of relativity, or the concept of immunization against disease. Nor can one obtain a copyright on the theme of Greek tragedy, in the Romeo and Juliet story; or in the idea of the impressionist painting. These basic elements of knowledge or inspiration are understood as belonging to the public, and must remain in the public domain. The same reasoning counsels that no one should be permitted to privatize the knowledge that collectively constitutes the field of paleontology. When government implements that principle by regulation governing excavation, use, and ownership of fossils of scientific importance so as to assure that knowledge is not lost to the public and to posterity, it acts appropriately as a public trustee, in accord with accepted public trust concepts.

Fossils present a distinctive (though not unique) setting for the application of the trust principle. Fossils are material objects that contain scientific knowledge within them or in their context. Unlike mathematical knowledge, or knowledge of a theory of physics, paleontological knowledge is embedded in a physical object and in a physical context. The information which the physical object contains is entitled to the same protection under the trust concept as is other knowledge—that is, it should be protected as a public good for public use and benefit. However, most knowledge, like the discoveries of mathematics, is not entwined with physical objects that superficially look like any ordinary object that can be held as private property. Therefore, some special rules are needed for the protection of objects like fossils that bear knowledge or ideas within material objects. While a significant vertebrate fossil and a lump of coal may seem to be similar objects that the laws of property would treat similarly, they are not. For example, there is no particular reason why coal or oil lying under the public lands should not become ordinary private property, to be disposed of at the will of a private owner, so long as the public is appropriately compensated.. But that is not at all the case with a scientifically important fossil found on the public lands (or, as we shall see, on private land either)..

Recognition of this unusual situation (knowledge physically contained within a material object) explains why the legal standing of scientifically valuable fossils needs to be differentiated from the legal status of other things found on or under the ground, such as coal or oil or diamonds, even though they may also be fossilized remains. (In this respect, scientifically valuable fossils are more analogous to archaeological remains found on the land than they are to other sorts of fossilized materials). This distinction between the mere material-object value of something from its scientific/educational value explains *why* federal statutes should declare objects such as scientifically valuable fossils to be in the public trust, and to protect them for their scientific and public value.

To implement the public trust principle as to paleontological knowledge, the law (law as used in the following pages refers to federal statutes) needs to separate out the merely material object-value of a fossil (and its setting) from its scientific value. The former (the material object-value) can properly be treated in whatever conventional ways objects on the particular public lands are treated; but the latter (scientific value) deserves to be safeguarded as an inalienable element of the public domain. This might at first seem a formidable task, but in practice it is not so difficult.

To take but one example, while significant fossil specimens no doubt belong in museums where they are available for scientific and public access, as far as public trust responsibilities are concerned, there should be no objection in principle to allowing casts to be made and marketed to collectors, so long as the work can be done without risk of damage to the specimen. Apparently there is considerable variation in policy among major museums today, some of which prohibit the making of casts, while others allow them solely for research purposes but not for sale, and still others permit marketing of casts, retaining a royalty payment to the institution that owns the original specimen. As to this latter point, nothing in public trust principle dictates how (or whether) economic benefits derived from such practices are allocated, so long as financial arrangements do not interfere with public access or with research.

Another example, though not involving public property, is familiar in American law: the historic preservation ordinance (1978). A private building designated as a landmark because of its historic or architectural values, may be used for ordinary private purposes–as a home, an office building, or a railway station–so long as the owner does not modify or demolish those elements of the building that have historic and/or architectural heritage value, such as the facade. While such ordinances are usually adopted on a local (municipal) level, and thus may vary from one place to another, they are generally quite consistent in permitting economically productive private uses so long as those uses are consistent with the historic or architectural values the ordinance aims to protect.

Yet a third technique, well developed in English law, employs a positive incentive approach to protecting public trust values in material objects. In that country individuals who inherit objects designated as having national heritage value (which objects may range from manuscripts, to furniture, paintings and stately homes) are immunized from payment of inheritance tax on the objects if they agree to make the objects accessible to the public on reasonable terms. Some owners open their houses on certain dates to public visits; some deposit paintings or sculptures in local museums at certain times; others, by special pre-arrangement, allow visitors to come to their homes (1999). It would be quite easy for the United States to adopt a variant of this approach addressed to private owners of important fossils (or other artefacts). For example, a procedure might instituted through which fossils of "national scientific significance" could be identified by a council of experts. Private collectors who owned such objects, and were willing to make them accessible to researchers and to the public on specified terms, could seek to have them certified as being of such significance. Upon certification, and upon making arrangements for access (for example, by loan to a major museum at certain intervals or for a certain time), the owner would qualify for a tax benefit. The benefit might consist of a charitable deduction, a partial exemption from estate tax (if it remains in effect), or some other such financial benefit. While the United States Treasury has generally been opposed to tax-benefit proposals that are not revenue-need-based, the fact remains that such devices are the most attractive non-coercive means to encourage private owners of publicly-valued objects to acknowledge the public interest in their collections.

In each of these otherwise diverse instances, the law has shown itself capable of sorting out those elements of an object's possession or use which relate only to its material-object value–whether recreational, economic, or familial—from those elements, such as transcendent scientific, artistic, or scholarly values, that define it as having public trust significance.

The techniques by which various nations acknowledge and protect public trust properties are numerous, and well established throughout the world. Export limitations are commonplace, where heritage items, such as antiquities or great works of art, have special significance to a national community (1989). Commonly certain objects cannot be sold out of the country until the government has had an opportunity to purchase it for a museum at home (though raising sufficient funds is often a formidable task). While the owner is ordinarily compensated, he/she is obliged at least to tolerate some delay, and thereby perhaps some diminution of international market opportunities, in order to assure protection of the public trust element in the property.

What is required in each such case is a legal regime that prohibits collection, possession, removal, or ownership in ways that diminish or destroy cultural or scientific value, or that interfere with scientific study of the object. If it is determined that the object has no discernible potential for scientific study or use (as may be the case with most non-vertebrate fossils, or other common fossils) or that such potential has been exhausted (a site has been fully studied and documented), then the object may appropriately be relegated to rules that generally govern ordinary property.

THE SHAPE OF A PUBLIC TRUST LEGAL REGIME FOR THE PUBLIC LANDS

What would a public trust regime for public domain paleontological resources look like? Basically, it would be similar to the recommendations set out in the May, 2000, Report of the Secretary of the Interior on Fossils on Federal and Indian Lands, and to the basic administrative rules that are now in place on the part of federal land management agencies, as summarized in that report (p. 20). It would, however, be appropriate to have a single federal paleontological protection statute, similar in scope and structure to the Archaeological Resources Protection Act (1979), setting out general public trust management principles for all federal agencies and federal lands. In brief, such a statute would:

- Declare that paleontological resources on the public lands have value for scientific study and research and education, both in themselves and in their context, and are held in public trust in order to protect and preserve those values.

- Provide for inventorying and monitoring of scientifically valuable sites.

- Provide for adequate enforcement to protect sites from unauthorized collection, and to penalize—at levels that are sufficient for deterrence—unauthorized collecting and disturbance of sites..

- Provide a permit system to restrict collecting so as to assure the safeguarding of scientific and educational values.

- Retain all scientifically valuable specimens in public ownership and house them in repositories so as to assure access in perpetuity for scientific study and public education.

• Subordinate private possession and use to public trust interests on a permanent basis, while permitting collection and possession of common fossils by amateurs on those federal lands where the governing mandates are consistent with such activity.

BEYOND THE PUBLIC LANDS

The foregoing discussion of public trust principles should make clear that the public interest in scientifically valuable paleontological resources does not vary, depending on where they are found. However, in the United States paleontological remains on private lands are generally treated as ordinary private property. (1993). The United States is unusual in this regard. Many–probably most—countries treat culturally or scientifically valuable relics, whether human-made or natural, as either an endowment belonging to the nation or, at least, as a limited sort of private property subject to regulatory regimes that protect the public trust interest it the object (1984). This is true not only of countries with quite different conceptions of private property, such as Turkey (1997), but also to nations with property systems very much like our own. For example, some Canadian Provinces designate all paleontological resources found within its territory as the property of the Province (1994b). While other countries usually provide some measure of compensation, as a reward or incentive, to finders or landowners, the United States is almost alone among nations in taking an essentially hands-off position as to such materials on private lands, unless they are human remains (1999).

Landownership of the site where fossils are discovered, however, should not be the *sine qua non* for public control of the fate of scientifically significant fossils. A wide range of legal strategies is potentially available for bringing private or tribal lands within the ambit of public trust protection. One might do as little as require public notification of proposed excavation activities, with a public right of first refusal to acquire authority to explore a site, to study and/or to collect significant fossils from it. Alternatively, laws can be enacted to establish a regulatory scheme governing registration and qualification of private entities engaged in fossil collection, limiting permission to properly trained and qualified persons, and regulating methods of excavation.

There is no reason to believe that modest regulatory restrictions of the sort suggested in the preceding paragraph would give rise to constitutional objections, either as to the scope of congressional authority or as to violation of private property rights. Federal authority to regulate interstate, international, and tribal commerce would undoubtedly be ample to regulate activities that result in trade and commerce in fossils by collectors and institutions. Nothing in the several recent U.S. Supreme Court cases (2000a; 1995a) confining the congressional commerce power to protection of things in interstate commerce, or having a substantial relation to interstate commerce, would put into question legislation governing the unquestioned national and international commerce in fossils growing out of excavations on private lands. Nor would such regulation transgress the constitutional prohibition on taking of private property for public use without the payment of just compensation. The reason is that regulation of the sort suggested above would neither constitute a total deprivation of value under the Supreme Court ruling in the *Lucas* case (1992) nor would the character of the government action or its economic impact violate the standards set down in the Court's *Penn Central* decision (1978).

In addition to, or instead of, the regulatory regime proposed here, Congress could employ any of a variety of positive incentives, such as tax credits for permitting scientific access and study, or for various forms of cooperation with public museums or universities. Even the most minimal such provisions would acknowledge recognition of the presence of a public trust interest in fossils notwithstanding their location and their ownership.

The passive position taken by the United States in regard to locations other than the federal lands apparently explains the view taken by the Department of the Interior that as to fossils found on Indian lands "it is up to the Indian landowner...to determine who has access to their lands and under what conditions..." and that the sole role of the Bureau of Indian Affairs is to review contracts or leases of Indian lands for the extraction of fossils to assure that they "are of economic benefit to the Indian landowner." (2000)(the Secretary's approval role has recently been further narrowed by Congress, see 25 U.S.C. § 81). Though the government is understandably and appropriately deferential to tribal legislative authority on reservation land (1996), its view of the government's "trust" obligation to Native Americans in purely economic terms, taking no account of the broader public trust interest in the fossils, whether on Indian land or elsewhere, is at best distressingly narrow, and reflects no inclination to find ways to accommodate the two distinctive trust-type obligations the United States bears, to tribal autonomy and to our common evolutionary heritage.

As a practical matter, failure to take cognizance of significant fossils wherever they may be found probably subverts any effort at effective enforcement even of fossil resources on the public lands. For example, usually one of the most effective ways to address unauthorized collecting/looting on public lands, is to implement a permit and registration system that can be followed to auction markets and other collector sale sites. Unless some sort of permitting or at least some registration system applies to non-federal lands as well as to the federal lands, leading to a certification-of-origin requirement, there is often no effective way of determining whether objects that move into the collector market have been illegally removed from the federal lands (1994). The Supreme Court has sustained laws based on this sort of need for administrative coherence in upholding a law governing trade in eagle feathers (1979a).

In any event, the notion that government is powerless to protect trust values found on private (or Indian) lands is dubious, both in law and in fairness. The well-established precedents for regulation of private owners of designated historic landmarks could certainly be adapted to lands containing valuable fossils. A recent modest proposal by an English expert for protection of buried antiquities could easily be adapted to this country and to fossils: The owner would have good title, but that title could only be secured by reporting the find, and securing the site for a specified period, with authority in a designated public authority to determine whether or how exploration could go forward, and in the event to provide compensation against loss, or to confirm the private title and right. Failure to report and to await a scientific judgment on further development would subject the owner to fines and penalties.

Implementation of even the most modest of such proposals would constitute a major step forward in implementation of the public trust in paleontological resources.

REFERENCES

1916. National Park Service Organic Act. 39 Statutes at Large 535. 16 U.S.C. §§ 1-4.

1965. Agate Fossil Beds National Monument. Public Law 89-33, 16 U.S.C. § 431.

1969. Florissant Fossils National Monument. Public Law 91-60, 16 U.S.C. § 431.

1970. Sax JL. The Public Trust Doctrine in Natural Resource Law: Effective Judicial Intervention. Michigan Law Review 68:471.

1970a. General Authorities Act. Public Law 91-383, 16 U.S.C. § 1a-1.

1972. Fossil Butte National Monument. Public Law 92-537, 16 U.S.C. § 431.

1975. Hells Canyon National Recreation Area Act. Public Law 94-199, 16 U.S.C. § 460gg

1976. Federal Land Policy and Management Act. Public Law 94-579, 43 U.S.C. § 1701(a)(8).

1978. Penn Central Trans. Co. v. New York City. 438 U.S. 104, 98 S.Ct. 2646, 57 L.Ed.2d 631

1979. Archeological Resources Protection Act. Public Law 96-95, 16 U.S.C. § 470aa et seq.

1979a. Andrus v. Allard. 444 U.S. 51, 100 S.Ct. 318, 62 L.Ed.2d 210.

1980. Selvin M.. The Public Trust Doctrine in American Law and Economic Policy, 1789-1920. Wisconsin Law Review 6:1403.

1980a. Alaska National Interest Lands Conservation Act. Public Law 96-487, 16 U.S.C. § 3191.

1984. O'Keefe PJ and Prott LV. Law and the Cultural Heritage. Volume I Abington, Professional Books, ch. 6.

1986. Knudson R. Contemporary Cultural Resource Management. In DJ Meltzer et al, editors. American Archaeology Past and Future. Washington: Smithsonian Institution Press. p. 395-413.

1987. National Research Council. Paleontological Collecting. Washington. National Academy Press.

1988. Federal Cave Resources Protection Act. Public Law 100-691, 16 U.S.C. § 4301 et seq.

1989. O'Keefe PJ and Prott LV. Law and the Cultural Heritage. Volume III Abington, Professional Books, ch. 9.

1991. Knudson, R. The Archaeological Public Trust in Context. In GS Smith & JE Ehrenhard, editors. Protecting the Past. Boca Raton: CRC Press, 3-8.

1992. Lucas v. South Carolina Coastal Council. 506 U.S. 103, 112 S.Ct. 2886. 120 L.Ed.2d 798.

1993. Black Hills Institute of Geological Research. 12 F.3d 737, 742 (U.S. Ct. of App. 8th Cir.).

1994. Lazerwitz DJ. Bones of Contention: The Regulation of Paleontological Resources on the Federal Public Lands. Indiana Law Journal. 69:601.

1994a. California Desert Protection Act. Public Law 103-433. 16 U.S.C.§ 410aaa

1994b. Sakurai DS. Animal, Mineral, or Cultural Antiquity?: The Management and Protection of Paleontological Resources. Loyola of Los Angeles International & Comparative Law Journal 17:197, 225, 228n.212.

1995. Knudson, R. The Public Trust and Archaeological Stewardship. In R Knudson and BC Keel, editors. The Public Trust and the First Americans. Corvallis: Oregon State University Press. p 9-28.

1995a. United States v. Lopez. 514 U.S. 549, 115 S.Ct. 549, 131 L.Ed.2d 626.

1996. Dussias AM. Science, Sovereignty, and the Sacred Text: Paleontological Resources and Native American Rights. Maryland Law Review 55:84.

1997. Özsunay E. Protection of Cultural Heritage in Turkish Private Law. International Journal of Cultural Property. 6:278.

1999. Sax JL. Playing Darts With A Rembrandt. Ann Arbor: University of Michigan Press. p. 66, 179.

2000. Fossils on Federal & Indian Lands. Report of the Secretary of the Interior. Washington, D.C. U.S. Department of the Interior. May 2000.

2000a. United States v. Morrison. 529 U.S. 598; 120 S.Ct. 1740, 1749, 146 L.Ed.2d 658.

2001. Code of Federal Regulations. 36:2.1, 2.5

2001a. National Park Service Management Policies. Chapter 4.

2001b. Code of Federal Regulations. 43:3.17; 43:8365.

2001c. http://dailynews.yahoo.com/h/nm/20010301/ts/afghan_statues_dc_4.html.

AN INVENTORY OF PALEONTOLOGICAL RESOURCES FROM THE NATIONAL PARKS AND MONUMENTS IN COLORADO

REBECCA SCOTT[1], VINCENT L. SANTUCCI[2], AND TIM CONNORS[3]

[1]Bodie State Historic Park, PO Box 515, Bridgeport, CA 93517;
[2]Fossil Butte National Monument, PO Box 592, Kemmerer, WY 83101;
[3]National Park Service, Geologic Resources Division, 12795 West Alameda Parkway, Academy Place, Room 480, Lakewood, CO 80227

ABSTRACT—The National Park Service (NPS) currently administers eleven park units within the state of Colorado. Most of these parks and monuments have been established and are recognized for their significant geologic features. Two monuments in Colorado, Dinosaur National Monument and Florissant Fossil Beds National Monument, were specifically established for their significant paleontological resources. Fossiliferous rocks of Paleozoic, Mesozoic, and/or Cenozoic age have been identified in all of the National Park System units in Colorado. In 2000, the first comprehensive inventory of paleontological resources in the national parks and monuments of Colorado was initiated. A wide diversity of fossilized plants, invertebrates, vertebrates, and trace fossils has been documented. Paleontological resources identified from within the parks and monuments have been assessed for their scientific significance, potential threats, and management as non-renewable resources. Baseline paleontological resource data obtained during this survey will assist National Park Service staff with management of the paleontological resources and protection of fossils within their park.

PALEONTOLOGICAL RESOURCE MANAGEMENT AND PROTECTION

The paleontological resources in the national parks and monuments of Colorado provide valuable information about ancient plants and animals and their environment. Fossils are recognized as non-renewable resources that possess both scientific and educational values. The NPS manages fossils along with other natural and cultural resources for the benefit of the public. All fossils from NPS areas are protected under federal law and their collection is prohibited except under the terms of a research permit.

Paleontological resources are exhibited in a number of national parks and monuments in Colorado. The Quarry Visitor Center at Dinosaur National Monument provides visitors with the opportunity to view the world famous dinosaur bone-bearing rock wall as an *in situ* exhibit. Several thousand macrofossils, representing 110 species, have been collected from Mesa Verde National Park and there are excellent displays of fossils at the park. Florissant Fossil Beds National Monument has an *in situ* exhibit of giant petrified stumps, *Sequoia affinis,* along an interpretive trail.

More comprehensive paleontological resource inventories are underway in a number of the NPS units in Colorado. These surveys are designed to identify the scope, significance, and distribution of the paleontological resources and to assess any natural or human-related threats to these ancient remains. Fossils reported from areas adjacent to the parks and monuments are also considered in this study in order to assess the potential for stratigraphically equivalent resources within park boundaries. Baseline paleontological resource data will enable park staff to enhance the management, protection, research and interpretation of park fossils.

Ongoing and future paleontological research in the various NPS units within the state of Colorado will expand our knowledge of the fossil record and the ancient environments in which these organisms lived.

BENT'S OLD FORT NATIONAL HISTORIC SITE

Bent's Old Fort National Historic Site (BEOL) was authorized on June 3, 1960 as a national historic site to preserve one of the important trading centers on the Sante Fe Trail. The site is one of the smaller NPS areas administered in Colorado. The fort is located on the flood plain of the Arkansas River in the southeastern part of the state.

Bedrock at Bent's Old Fort consists of Cretaceous rocks identified as the Bridge Creek Member of the Greenhorn Limestone Formation. The Greenhorn is overlain by approximately twelve feet (3.6 m) of Pleistocene (Wisconsinan) sands and gravel deposited between 11,000 and 8,000 years ago. This unit is overlain with clayey sand that is also of Wisconsin age (Moore, 1973).

Twenty-eight specimens of the rudist *Durania cornupastoris* were collected from the Bridge Creek Member of the Greenhorn Limestone just outside the park boundaries

(Cobban et al., 1985). Rudists are an extinct group of bivalved (pelecypod) mollusks. The rudist-producing bed in the Bridge Creek Member extends into the national historic site; thus, the potential for this resource in the park also exists.

A fragmentary mammoth tusk was discovered at Bent's Old Fort by Jackson Moore, a NPS archeologist. Tusk fragments were collected by Jackson between 1963 and 1966. The remains were found in a gravel bed overlying a white limestone unit at the historic site (Moore, 1973). The fragments have been tentatively identified as *Mammothus columbi* (personal communication, Nancy Russell, 2000). According to the park's museum records, an additional three mammoth tusk fragments were found in 1992 by archeologist Jerry Dawson.

BLACK CANYON OF THE GUNNISON NATIONAL PARK

Black Canyon of the Gunnison (BLCA) was originally proclaimed a national monument on March 2, 1933, to preserve a twelve mile stretch of river gorge carved by the Gunnison River in west-central Colorado. The Monument was given wilderness designation on October 20, 1976 and was later redesignated as a national park on October 21, 1999.

Hansen (1987) provides a comprehensive overview of the geology of Black Canyon of the Gunnison National Park. Hansen (1971) published a geologic map, which includes the national park. During 1999 and 2000, the National Park Service Geologic Resources Division produced a digital geologic map for BLCA, compiling maps by Hansen, at 1:24,000 scale.

The geologic setting of BLCA consists of a sequence of Precambrian rocks including arkosic sandstones, graywackes, and granite (Hansen, 1967). Renewed crustal movement in the area accompanied the intrusion of the Vernal Mesa and Curecanti plutons (Hansen, 1981). Most of the Paleozoic section in the park has been eroded away before or during the time of the Uncompahgre uplift. The only evidence of Paleozoic rocks in the canyon are diabase dikes dating to the Cambrian or Ordovician.

During the Jurassic, sediments accumulated on the older Precambrian rocks in the Black Canyon area. The Entrada, Wanakah, and Morrison formations preserve Jurassic paleoenvironments in the park, but these are poorly exposed within BLCA. Fiorillo (1996) reports on a Morrison Formation vertebrate locality within the boundaries of BLCA with the most significant fossil locality being a badly weathered sauropod bone impression found on the North Rim (Fiorillo, 2001, personal communication). One locality in the Salt Wash Member of the Morrison Formation, located just outside of the park, has yielded fragments of a theropod posterior caudal vertebra, a sauropod rib, and numerous other dinosaur bone fragments (Anonymous, 1990).

Overlying the Morrison Formation are the Cretaceous Burro Canyon Formation, Dakota Formation and Mancos Shale (Hansen, 1971). A few marine invertebrate fossils are known from the Mancos Shale in the park. A series of Tertiary volcanic eruptions covered the area with lava flows, breccias, and tuffaceous deposits including the West Elk Breccia (Fig. 1).

COLORADO NATIONAL MONUMENT

Colorado National Monument (COLM) was established by presidential proclamation on May 24, 1911. The Monument is located in the west-central portion of Colorado along the eastern margin of the Colorado Plateau and preserves scenic sheer-walled canyons and towering monoliths.

COLM contains rocks dating from the Precambrian to the Cretaceous. Basement rock consists of Precambrian schist and gneiss. During the Paleozoic, the area was uplifted forming the Uncompahgre Highlands. Precambrian rocks are overlain by Mesozoic sedimentary units including, from oldest to youngest, the Chinle Formation, Wingate Sandstone and Kayenta Formation. The Triassic Chinle Formation is the oldest sedimentary formation in the COLM and unconformably overlies Precambrian crystalline rocks, reflecting a major unconformity. All of the sedimentary units in the park are Mesozoic. A theropod track site was discovered in the Chinle Formation in 1990 (A. Hunt, personal communication, 1999). The *Grallator*-like track site is located near the east entrance to the Monument.

Where the Kayenta has been removed; the Wingate Sandstone weathers into rounded domes and forms most of the named features within the Monument (Dubiel, 1992). The Entrada Sandstone of the Jurassic San Rafael Group is usually salmon colored and crossbedded: it is topped by the Wanakah. The Entrada Sandstone of Rattlesnake Canyon has been referred to as the second largest concentration of arches in the world and is of a different origin than the arches at Arches National Park. The Morrison Formation overlies the San Rafael Group and is fossiliferous. The Morrision Formation consists of the Tidwell, Salt Wash and the Brushy Basin Member (Turner and Fishman, 1991). The Jurassic section is topped by the Cretaceous Burro Canyon Formation and Dakota Sandstone (Fig. 2).

In 1900, a famous dinosaur discovery was made in an area just outside of the current boundary of COLM. Elmer Riggs uncovered the forelimb of a sauropod dinosaur (*Camarasaurus grandis*) in the Brushy Basin Member of the Morrison Formation (Armstrong and Kihm, 1980). The site is marked today with an historic marker and is a local tourist stop known as Dinosaur Hill.

During 1977, an inventory of the Morrison Formation in COLM documented fourteen fossil localities (Callison, 1977). Fossils identified during the inventory included bivalves, gastropods, turtles, crocodilians, and dinosaurs, including an ischium of a dryosaur. Most of the specimens were found in the lower Salt Wash Member or Brushy Basin Member of the Morrison Formation. In 1985, many of these sites were resurveyed by George Engelmann yielding unionid bivalves, gastropods, and a sauropod caudal vertebra (Armstrong and Kihm, 1980). Engelmann and Fiorillo (2000) resurveyed these sites again in 1995 and reported several

FIGURE 1. Stratigraphy of Black Canyon of the Gunnison National Park and Curecanti National Recreation Area.

Stratigraphy of Black Canyon of the Gunnison National Park and Curecanti National Recreation Area, Colorado

Era	Period	Epoch	Formation Member	Map Unit	Description
Cenozoic	Quaternary	Holocene	Alluvium, talus, landslides	Qab	succession of silty sands and gravels, mostly derived locally, underlain by well-rounded, well-sorted stream gravels derived largely from volcanic terraces in the San Juan Mountains.
	Tertiary	Miocene and Pliocene	Hinsdale	Th	Medium- to dark-gray aphanitic slightly vesicular to scoriaceous intermediate (dacite) flow remnants Maximum thickness about 150 feet.
		Oligocene	Carpenter Ridge Tuff	Tcr	Very light gray platy devitrified welded or partly welded tuff; at the base, dark-brown vitrophyre. Maximum thickness about 220 feet.
			Fish Canyon Tuff	Tfc	Light-gray crystal-rich (<45 percent) loosely welded tuff containing predominant fragmented crystals of plagioclase and subordinate sanidine, biotite, quartz, oxyhornblende, and sparse pale-green clinopyroxene.. Maximum thickness about 300 feet.
			Sapinero Mesa Tuff	Tsm	Mostly reddish-brown devitrified welded tuff grading upward into non-welded tuff. At the base, black vitrophyre 20-50 feet thick containing abundant reddish-brown spherulites, commonly underlain by gravel. Thickness commonly about 80-180 feet.
			Dillon Mesa Tuff	Tdm	Mostly light-brown slightly porphyritic moderately welded tuff, locally with 10-20 feet of dark-brown vitrophyre at base, commonly underlain by gravel. Generally less than 80 but locally as much as 180 feet thick.
			Blue Mesa Tuff	Tb	Reddish-brown devitrified densely-welded vitric lapilli ash tuff;
			West Elk Breccia	Twa	Ash-flow tuff lens, locally welded, as much as 200 feet thick.
Mesozoic	Cretaceous	Upper	Mancos Shale	Km	Dark-gray silty clay shale containing scattered lenses of friable gray sandstone and scattered calcareous siltstone concretions. Plastic when wet and susceptible to failure. Section incomplete but as much as 2,200 feet thick near axis of Montrose syncline and beneath Cathedral Peak.
		Lower	Dakota Sandstone	Kdb	mostly light-gray fine to very fine grained platy sandstone, commonly quartzitic, and dark-gray papery carbonaceous shale; coalbeds near base; minor conglomeratic sandstone. Ripple marks common toward top. Forms dip slopes.
			Burro Canyon	Kdb	chiefly very light gray cross-bedded cliff-forming conglomeratic sandstone and pebbly conglomerate. Discontinuous beds of light-gray shale.
	Jurassic	Upper	Morrison: Brushy Basin	Jm	chiefly varicolored red, lavender, green, and light-gray bentonitic mudstone and silty shale, gray to lavender massive siltstone, and fine-grained light-gray sandstone. Mudstone plastic when wet. Pebble conglomerate containing red and green chert pebbles, and locally dinosaur bone, about 140 feet below top. Member is about 315-360 feet thick.
			Morrison: Salt Wash	Jm	chiefly light-gray massive to cross-bedded fine-grained cliff-forming sandstone interbedded with red silty shale. Sandstone beds lenticular fill channels. Member is about 110-175 feet thick.
			Wanakah: Junction Creek Sandstone	Jj	Light-gray to light-brown, fine- to medium-grained, quartzose sandstone; massive, thick-bedded, weakly crossbedded; tightly cemented and quartzitic in upper part. Maximum thickness about 180 feet. (
			Wanakah: Pony Express Limestone	Jwj	discontinuous, locally brecciated fetid pellatal to aphanitic silty gray limestone 1-7 feet thick. Nonexistent east of Dead Horse Mesa.
			Entrada	Je	very fine grained friable indistinctly cross-bedded eolian sandstone. Basal conglomerate 1-5 feet thick contains abundant fragments of locally derived Precambrian rock
Precambrian	Proterozoic		Pegmatite	Pcp	Very coarse variably grained dikes and sills
			Curecanti Quartz Monzonite	pCc	Light-gray to orange-pink, medium-grained sodic quartz monzonite or granite.
			Vernal Mesa Quartz Monzonite	pCv	pinkish-gray very coarse grained porphyritic weakly to strongly foliated quartz monzonite near to granodiorite in composition.
			Pitts Meadow Granodiorite	pCpv	dark medium-grained variably foliated quartz diorite and diorite.
			Metamorphic rocks	pCa	Dark lineated medium-to coarse-grained schist

Summarized from "**Geologic Map of the Black Canyon of the Gunnison River and Vicinity, Western Colorado**" by Wallace R. Hansen, 1971; scale 1:31,680;USGS Miscellaneous Investigations Series Map I-584 ***NOTE: squiggly lines represent unconformities (major breaks in the geologic record)***

FIGURE 2. Stratigraphy of Colorado National Monument.

Bedrock Stratigraphy of Colorado National Monument, Colorado

Era	Period	Epoch	Formation	Member	Map Unit	Description
Mesozoic	Cretaceous	Upper	Mancos Shale		Km	medium-dark-gray, dark-gray, brownish-gray, and brownish-black fissile shale that forms gentle slopes, which are broken at wide intervals by thin, brownish-gray sandstone ledges and sparse, white bentonite beds. Only the lowermost Mancos Shale is exposed along the northern boundary of the map area near the Colorado River. This lowermost Mancos was deposited in a shallow marine subtidal setting, similar to the modern Texas Gulf Coast.
Mesozoic	Cretaceous	Upper and Lower ?	Dakota		Kd	Sandstone and conglomerate forming prominent and resistant ledges and ridges, whereas mudstone and interbedded sandstone and shale generally form slopes. The Dakota Formation caps Black Ridge near the central western boundary of the map area and forms a series of low hogbacks in the Redlands area south of the Colorado River. Locally in the Redlands area, dinosaur tacks are preserved in sandstone beds.
Mesozoic	Cretaceous	Lower	Burro Canyon		Kb	in most localities, the upper part is dominated by mudstone and forms slopes, whereas the lower third to two-thirds of the unit is dominated by sandstone and forms cliffs.
Mesozoic	Jurassic	Upper	Morrison	Brushy Basin	Jmb	multicolored mudstone forming gentle rounded slopes. The Brushy Basin Member was deposited in a mud flat to saline lacustrine setting (Turner and Fishman, 1991) characterized by associated highly sinuous fluvial systems. Volcanic basins in New Zealand are possible modern-day analogs.
Mesozoic	Jurassic	Upper	Morrison	Saltwash	Jms	sandstone-rich cliff-forming unit sandwiched between the mudstone-rich, slope-forming Brushy Basin and Tidwell Members of the Morrison Formation. The Salt Wash Member was deposited in a fluvial setting including associated flood plains and shallow ponds. The architecture of the channel-form sandstone bodies suggests that the fluvial channels were relatively thin (1 to 7 m), narrow (5 to 30 m), and moderately sinuous. An analog for this depositional setting exists where rivers empty into the modern-day Texas Gulf Coast.
Mesozoic	Jurassic	Upper	Morrison	Tidwell	Jmt	mudstone-rich; forms slopes that are broken by relatively thin ledges of sandstone and limestone; with rare exception, this is the only limestone in the map area. Within the Tidwell Member, the character and thickness of mudstone, sandstone, and limestone change significantly laterally.
Mesozoic	Jurassic	Middle	Wanakah		Jw	mudstone-rich, slope-forming; recognized easily by its distinctive green-over-red colors and by a noticeable reduction of vegetation. The depositional setting for the Wanakah is nonmarine mudflat and (or) shallow lacustrine environment.
Mesozoic	Jurassic	Middle	Entrada	"Board beds" unit	Jeb	interbedded resistant sandstone and less resistant mudstone form slabby exposures that resemble a stack of boards, giving the "board beds" unit its informal name. This unit was deposited in a wet sand flat environment in a coastal setting. The western coast of Baja California, Mexico, at Guerrero Negro, may be a possible modern-day analog (Fryberger and others, 1990).
Mesozoic	Jurassic	Middle	Entrada	Slick Rock Member	Jes	forms a conspicuous pale-orange, ribbon-like cliff or rounded bench that is almost totally free of vegetation below its white cap of the "board beds" unit.
Mesozoic	Jurassic	Early	Kayenta		Jk	commonly forms resistant ledges above the cliff-forming Wingate Sandstone (Jwg) and also forms cliffs in several areas. Sandstone is present throughout the Kayenta, whereas conglomerate and mudstone are found mainly in the upper half.
Mesozoic	Jurassic	Early	Wingate Sandstone		Jwg	forms the magnificent 100-m-high, orange cliffs that give the Colorado National Monument its most spectacular vistas.
Mesozoic	Triassic	Late	Chinle		TRc	distinct red slopes underlie the towering cliffs of the Wingate Sandstone (Jwg), and in turn, rest on the great angular unconformity on dark Proterozoic basement rocks.
Precambrian	Proterozoic	Early	Meta-igneous gneiss		Xi	metamorphosed granite that contains minor xenoliths of host rock and is exposed chiefly in the eastern part of Ute Canyon. Meta-igneous bodies in and near Ute, Red, Columbus, and Gold Star Canyons are probably part of a single pluton, here called the Ute Canyon stock.
Precambrian	Proterozoic	Early	Migmatitic meta-sedimentary rocks		Xm	consist of a complexly folded mixture of dark schist and light migmatitic pegmatite found in the bottoms of most of the canyons at the Monument.

*Summarized from "**Geologic Map of Colorado National Monument and Adjacent Areas, Colorado**" by Robert Scott, 2001; scale 1:24,000;*
USGS Miscellaneous Investigations Series Map I-2740
NOTE: squiggly lines represent unconformities (major breaks in the geologic record)

new sites. Only one of the original sites inventoried in 1977, specifically the site adjacent to the Black Ridge Trail, appears to have been vandalized (Engelmann, personal communication, 2000).

A historic newspaper clipping in the COLM files indicates that a mastodon tooth was found in 1965 in Thoroughfare Canyon. The tooth was reportedly discovered by Dr. Jack Roadifer, a local geologist. The whereabouts of the specimen are currently unknown.

Ichnofossils in COLM, all of which occur in the Chinle Formation, include *Scoyenia gracilis, Koupichnium nopsca* and *Camborygma* (Hasiotis, 1997), crayfish burrows, and plant roots (rhizoliths. Horseshoe crab traces were discovered in the lower units of the Tidwell Member of the Morrison Formation (Hasiotis et al., 1996), representing the first report of these traces from Jurassic rocks.

CURECANTI NATIONAL RECREATIONAL AREA

Curecanti National Recreational Area (CURE) has been administered under a cooperative agreement between the Bureau of Reclamation and the NPS since February 11, 1965. The site contains three reservoirs: Morrow Point Lake, Crystal Lake, and Blue Mesa Lake. Blue Mesa Lake is the largest lake in Colorado with a surface area of 14 square miles.

The geologic setting is similar to that of the Black Canyon of the Gunnison. The park is recognized for having exposures of rocks that date to over 1.7 billion years in age, making these rocks among the oldest in western North America. (Fiorillo and Harris, 2000) (Fig. 1).

The Brushy Basin Member and the Salt Wash Member of the highly fossiliferous Upper Jurassic Morrison Formation are exposed at CURE. Trujillo (2000) prepared a detailed report documenting the paleontological field activities undertaken at the Dino Cove locality at CURE where the remains of two dinosaur taxa have been recovered from the Morrison Formation. The remains have been identified as a sauropod (cf. *Apatosaurus* sp.) and the theropod *Allosaurus* sp. (Fig. 3) (Fiorillo et al., 1995, 1996). There is a reptilian caudal vertebra in the park museum collection (Frank, personal communication, 2000). Conchostracans are very abundant in the Morrison at Curecanti, one location is Dino Cove (Fiorillo and May, 1996). There are several types of ichnofossils preserved within the Morrison Formation at CURE including crayfish burrows, termite nests, root casts and unionid clam burrows found near Red Creek (Fiorillo and Harris, 2000; Fiorillo, 1999; Fiorillo and McCarty, 1996). The invertebrate trace fossils predominantly occur in sandstone layers and suggest that during periods of non-deposition there were an abundance of small life forms (Fiorillo, 1999).

The first collection of Pleistocene (Rancholabrean) vertebrate remains from western Colorado come from Haystack Cave, located just outside of the CURE boundary. Specimens include remains identified as cf. *Miracinonyx trumani*, *Equus* sp. and *Phenacomys intermedius* (Emslie, 1986; Jefferson, personal communication, 2001; see Appendix A).

FIGURE 3. Dinosaur excavation at Curecanti National Recreation Area.

DINOSAUR NATIONAL MONUMENT

Dinosaur National Monument (DINO) was established by presidential proclamation on October 4, 1915. The site was originally established to protect the famous dinosaur quarry discovered in the Upper Jurassic Morrison Formation by Carnegie Museum paleontologist Earl Douglass. The Monument was enlarged in 1938 to include the spectacular canyons cut by the Green and Yampa Rivers.

Although the dinosaur-producing Morrison Formation has been the principal focus at DINO, the geologic record extends from the Precambrian through the Cretaceous. For more information on the geology of DINO, see Gregson and Chure (2000), Untermann and Untermann (1954, 1969), Hansen et al. (1983), and Hansen (1996).

The oldest sedimentary rocks within DINO are in the Precambrian Uinta Mountain Group. Hansen (1996) reported on fossilized algal globules *Chuaria* sp. from the Uinta Mountain Group near Manila, Utah, about 70 miles north of the Monument. Thus there is a potential for these fossils in the Monument.

The Upper Cambrian Lodore Formation consists of variegated, glauconitic shales and sandstones that contain marine invertebrates and trace fossils. Brachiopods, gastropods, and trilobites have been identified from the Lodore Formation in DINO (Herr, 1979; Herr et al., 1982; Hansen, 1996).

Corals, brachiopods, gastropods, and echinoderms are preserved, but rare, in the Lower Mississippian Madison Limestone (Hansen et al., 1983). Upper Mississippian brachiopods, fish, and coal beds are present in the Doughnut Formation (Hansen et al., 1983). The Lower Pennsylvanian Round Valley Limestone contains bryozoans, brachiopods, mollusks, and echinoderms (Hansen et al., 1983). Sponge spicules, corals, brachiopods, echinoid spines, crinoids, foraminifera, and conodonts are common in the marine facies of the Middle Pennsylvanian Morgan Formation (Driese, 1982).

The Permian Park City Formation (equivalent to the Phosphoria Formation farther north) consists of limestone, sandstone, and some chert layers (Fig. 4). Marine invertebrates including brachiopods, bivalves, cephalopods, gastropods, and other invertebrates have been found in this unit (Hansen et al., 1983).

Peabody (1948) studied some unusual reptile tracks in the Lower Triassic Moenkopi Formation in the vicinity of DINO. These include some swimming traces now in the collections of the Utah Field House Museum of Natural History in Vernal, Utah. *Scoyenia* traces have been reported from the Moenkopi at DINO (Lockley et al., 1990).

In the 1960's an important vertebrate tracksite was discovered just northeast of DINO. Today over two dozen tracksites have been identified within the Monument. Numerous tracksites have been discovered in the Upper Triassic Popo Agie and Chinle Formations. Fossil tracks are diverse and include those identified from dinosaurs, mammal-like reptiles, phytosaurs, aetosaurs, lepidosaurs, trilophosaurs, and tanystropheids (Lockley et al., 1990, 1992a, 1992b, 1992c; Hunt et al., 1993). Among these is a swimming trackway of *Gwyneddichnium* that shows webbing between the toes. In addition, there are examples of both walking and swimming types of these tracks. Horseshoe crab-like tracks and petrified wood are documented from the Chinle Formation at DINO.

Tridactyl theropod tracks and a rich *Otozoum* tracksite are known from the Lower Jurassic Glen Canyon Sandstone, which is equivalent to the Glen Canyon Group farther south and the Nugget Sandstone farther west and north (Lockley et al., 1992a; Santucci et al., 1998). The Middle Jurassic Carmel Formation is a shallow marine deposit that locally contains gypsiferous beds. Bivalves, gastropods, echinoderms, and a few rare tridactyl vertebrate tracks have been reported from the Carmel Formation near DINO.

Chure (1993) reported on three plesiosaur specimens that may have been collected from the Redwater Member of the Stump Formation (Middle to Upper Jurassic) near the western boundary of DINO. Belemnites, ammonites, gastropods, and bivalves occur in the Middle Jurassic Curtis Member of the Stump Formation in the DINO area.

The Upper Jurassic Morrison Formation is widely recognized as one of the most prolific dinosaur-bearing units in the world. In addition to dinosaurs, the Morrison Formation has produced important collections of Jurassic mammals and other vertebrates (Chure and Engelmann, 1989). The Morrison Formation at DINO contains four members including, from oldest to youngest, the Windy Hill, Tidwell, Salt Wash, and Brushy Basin Members (Turner and Peterson, 1999).

Utah's first theropod dinosaur (also recognized as the second dinosaur discovered in Utah) was found in 1870 near what is today DINO (Marsh, 1871; Bilbey and Hall, 1999). Earl Douglass made his famous discovery of the dinosaur bonebed in 1909. Under Douglass' direction the Carnegie Museum worked the site until 1922. During 1923, the U.S. National Museum (Smithsonian Institution) paleontologists collected a specimen of *Diplodocus,* which was mounted for display in that museum (Fig. 5). In 1924, the University of Utah collected a skeleton of *Allosaurus* from the quarry. Holland (1912, 1915, 1916, and 1924) and Gilmore (1924, 1925a, 1925b, 1926, 1932, 1936a, and 1936b) published extensively on the dinosaur discoveries from DINO.

FIGURE 5. Paleontologist Earl Douglass during the excavation of a Diplodocus skeleton in the Douglass Quarry at Dinosaur National Monument, circa 1923).

Theodore White was hired as the Monument's first paleontologist in 1953. White focused his attention on the preparation of the *in situ* bone-bearing layer and talking with the public about the world of dinosaurs. He hired and trained two maintenance men, Tobe Wilkins and Jim Adams, to expose in relief the bones on the Carnegie Quarry cliff face. White published both scientific and popular articles about the fossils at DINO (White, 1958, 1964). White liked to call himself the "Chief Ramrod of the Hammers and Chisels" until his retirement in 1973 (Ann Elder, written communication, 1999). Russ King, Dan Chure, Ann Elder, and Scott Madsen have recently worked as staff paleontologists at DINO (Chure, 1987, 1992; Chure and McIntosh, 1990). Elder (1999) provides an historical overview of the Carnegie Quarry at DINO.

Between 1989 and 1992, George Engelmann conducted a comprehensive paleontological survey of the Morrison Formation at DINO (Engelmann, 1992). More than 270 fossil sites were recorded during the survey. Most of the sites were dinosaur bone localities, but sites containing plant remains, invertebrates, and small vertebrates were also reported.

A number of new dinosaurs have been collected in recent years from DINO. In 1990, the first large carnivorous theropod dinosaur was collected from the Salt Wash Member of the Morrison Formation (Chure and Madsen, 1993; Chure et al., 1993). Chure (1994) reported on the oldest known troodontid dinosaur that was recovered from the Monument. A partial skeleton of a hatchling dinosaur, identified as *Camptosaurus*, was discovered at the Monument in 1991 (Chure et al., 1992) and represents the only hatchling of this genus known in the fossil record.

Chure et al (1989) reported on non-mammalian vertebrates collected from the Brushy Basin Member of the Morrison in DINO. Evans and Chure (1999) reported on lizards from the Morrison Formation that were collected in the Monument. The remains of the turtle *Glyptops* sp. and the crocodile *Goniopholis* sp. have been collected from the Monument. Several tiny frog skeletons and many isolated frog bones have been collected from a Brushy Basin microvertebrate locality in DINO. These amphibian remains

FIGURE 4. Stratigraphy of Dinosaur National Monument.

Stratigraphy of Dinosaur National Monument, Colorado and Utah

Era	Period	Epoch	Formation Member		Map Unit	Description
Cenozoic	Quaternary	Holocene	Alluvium		Qa	Poorly sorted gravel, sand, and silt of floodplain deposits, islands, and bars in river channels, bouldery debris fans and alluvial fans, and silty sandy gravel fills along minor tributaries.
			Eolian sand		Qe	Sand derived chiefly from Weber and Glen Canyon sandstones, and Browns Park Formation.
		Holocene and Pleistocene	Talus and colluvium		Qtc	Talus: accumulations of coarse angular rock fragments below cliffs and steep slopes. Colluvium: heterogeneous mixes of soil (engineering sense) and rock; grades into alluvium.
			Landslide deposits		Ql	Heterogeneous rock fragments and soil including blocks and (or) slabs of rock many meters long.
		Pleistocene	Older Alluvium		Qoa	Gravel and sand capping terraces and pediments of several different ages at varied heights above present drainage.
	Tertiary	Miocene	Browns Park		Tbp	Sandstone (predominant); limestone (subordinate); conglomerate (rare in map area)
		Oligocene	Bishop Conglomerate		Tb	Conglomerate and sandstone derived from Paleozoic limestones and Proterozoic Uinta Mountain Group. Pebble-size red chert common. Caps mesas and fills old valleys.
Mesozoic	Cretaceous	Upper	Mancos Shale	Main Body	Kms	Dark gray, expansive, fossiliferous calcareous shale with minor siltstone, sandstone (in upper half) and layered bentonite (in lower half). A few thin beds of limestone in lower part. Forms slopes, valley bottoms, and badlands.
				Frontier Sandstone	Kmf	Upper: calcareous, crossbedded, ripplemarked sandstone; marine fossils, coal; forms hogbacks and flatirons. Lower: Shale and siltstone, calcareous, silty, fossiliferous. Lower part forms slopes and saddles.
		Lower		Mowry Shale	Kmm	Bentonitic, dark, siliceous, fissile Shale; abundant fish scales; weathers silvery gray. Forms slopes and strike valleys.
			Dakota Sandstone		Kd	Sandstone, light-gray to light-yellow, medium- to coarse-grained, pebbly, crossbedded, ripplemarked, fluviatile; subordinate chert-pebble conglomerate and dark-gray shale. Forms hogbacks and dipslopes.
			Cedar Mountain		KJcm	non-marine multicolored claystone, siltstone, and fluviatile sandstone. Lavender tints prevalent in Cedar Mountain; distinctive chert-pebble Buckhorn Conglomerate Member marks its base. Morrison contains fluviatile conglomeratic sandstone, including the renowned dinosaur-bearing beds at the fossil quarry, and fresh-water limestone. Claystone, siltstone, and shale are regarded as overbank floodplain deposits. Unit forms slopes and is slide prone.
	Jurassic	Upper	Morrison			
			Stump	Redwater	Jsr	Soft, marine, fissile, glauconitic green siltstone and shale, sparse interbeds of crossbedded glauconitic oolitic fossiliferous marine limestone and sandstone. Forms slopes.
		Middle		Curtis	Jsc	Sandstone, light-gray to light-greenish gray, crossbedded, locally ripplemarked, fossiliferous, marine. Forms ledges.
			Entrada		Je	Pink-gray sandstone, fine- to medium-grained, thick-bedded, crossbedded, eolian. Forms cliffs.
			Carmel		Jca	Shale, siltstone, and mudstone, dark-red, sandy, marine; some fine- to medium-grained sandstone; a few thin beds of marine limestone. Forms slopes and saddles.
		Lower	Glen Canyon Sandstone		JTRg	Fine-grained sandstone. Large-scale eolian cross bedding deposited by winds that blew from north and northeast (Poole, 1962). Forms large sculptured outcrops, occasional cliffs.
	Triassic	Upper	Chinle	Main Body	TRc	Siltstone, shale, sandstone, and conglomerate, vari-colored, fluviatile; lacustrine or paludal ocherous marlstone, sandstone, and conglomerate. Forms slopes.
				Gartra Member	TRcg	Sandstone, pale-yellowish gray to tan to pink, coarse-grained to conglomeratic, generally thickly bedded crossbedded, fluviatile. Truncates and channels underlying Moenkopi Formation. Forms cliffs, benches, and rimrocks.
		Lower	Moenkopi		Trm	Siltstone and shale, vari-colored; gypsiferous toward base and in middle section; ripplemarks. Shoreward marine, possibly a tidal-flat deposit. Forms slopes, but a few resistant siltstone beds near middle form ledges or low cliffs.
Paleozoic	Permian		Park City	Upper	Ppu	Limestone, siltstone, sandstone, and dolomite, mostly nonresistant, thin-bedded, locally fossiliferous, marine. Ledge-forming phosphatic dolomite or limestone bed 3-10 m below top (Schell and Yochelson, 1966). Forms slopes.
				Lower	Ppl	Sandstone, dolomite, and limestone, cherty, locally phosphatic and fossiliferous, unevenly bedded, marine. Resistant, forms long dipslopes and caprocks on cliffs. In places sharply truncates cross bedding of underlying Weber Sandstone; in other places, contact is vague.
	Pennsylvanian	Middle	Weber Sandstone		PNw	very thickly bedded sandstone. Large-scale eolian crossbeds separated by diastems; deposited by winds that blew chiefly from the north (Fryberger, 1979). Rugged outcrops; the prime cliff-former in Dinosaur National Monument.
			Morgan	Upper	PNmu	crossbedded to planar bedded to massive, well-cemented Sandstone, and cherty fossiliferous marine limestone. Locally some sandstone is gray and Weber-like. Individual beds < 1 m to several meters thick.
				Lower	PNml	Shale, siltstone, interbedded sandstone and fossiliferous limestone. Forms slopes mantled with colluvium; slide prone.
		Lower	Round Valley Limestone		PNrv	Limestone, thick-bedded, cherty, fossiliferous, marine, and thin partings of gray to red shale. Pink to red chert in nodules and irregular masses, occasionally replacing fossils. Forms cliffs, ledges, and long dipslopes.
	Mississip-pian	Upper	Doughnut Shale		Mdh	Shale; largely marine, but has non-marine deposits in adjacent areas. Poorly exposed; plastic when wet, slide prone.
			Humbug			Sandstone interbedded with marine limestone and shale. Forms ledgy slopes, but locally makes good cliff exposures.
		Lower	Madison Limestone		Mm	Limestone, thick-bedded and unevenly bedded; nodular gray chert; locally dolomitic, sparsely fossiliferous, marine. Forms massive cliffs, ledgy toward top, and dipslopes. Locally is cavernous.
	Lower Ordovician or Upper Cambrian		Dike		Ocd	Leucitite, aphanitic, slightly microporphyritic. Ground mass crowded with disseminated hematite, rutile, and anatase (George A. Desborough, U.S. Geol. Survey, written commun., 1979)
	Cam brian	Upper	Lodore		Cl	ledge-forming sandstone, underlain by glauconitic marine sandstone. Basal contact uneven, and in Whirlpool Canyon, boss-like masses (fossil sea stacks) of Uinta Mountain Group protrude up into the formation. upper shaly unit has been wholly or partly removed by pre-Mississippian erosion and the thickness of the formation varies accordingly.
Precambrian Proterozoic Y			Uinta Mountain Group		Yu	Sandstone, some quartz & metaquartzite pebble conglomerate; some silty shale and (or) siltstone with micaceous bedding planes. Forms cliffs and ledges. Shale with micaceous bedding planes, and (or) siltstone, interbedded with fine- to coarse-grained red sandstone.

Summarized from "**Geologic Map of Dinosaur National Monument and Vicinity, Utah and Colorado**" by Wallace R. Hansen, Peter D. Rowley, and Paul E. Carrara, 1983; scale 1:50,000;USGS Miscellaneous Investigations Series Map I-1407

NOTE: squiggly lines represent unconformities (major breaks in the geologic record)

represent at least four different species of frogs including *Comobatrachus* sp., *Eobatrachus* sp., and a new pipoid anuran (Henrici, 1992, 1993, 1998).

Engelmann et al (1989) reported on microvertebrates, including mammals that have been collected from quarries in DINO. The quarries are in the Brushy Basin Member of the Morrison and have yielded hundreds of isolated teeth and a few partial jaws. The skull of a new multituberculate, *Glirodon grandis,* was also found at the Monument (Engelmann and Callison, 1999). Other mammals identified include a triconodont, a symmetrodont, at least two species of dryolestids, and a paurodontid.

Yen and Reeside (1950) described freshwater mollusks from the Morrison Formation. Sohn and Peck (1963) identified the ostracode *Theriosynoecum wyomingense* as a guide fossil to the Salt Wash Member of the Morrison Formation.

Ash (1993, 1994) reported on an unusual leaf *Czechanowskia* sp. from the Brushy Basin Member of the Morrison Formation in the Monument. This plant is considered by some as an indicator of humid paleoclimates, but, the discovery of this plant in deposits of an alkaline-saline lake farther south brings this interpretation into question (Turner and Fishman, 1991). A gingko leaf locality occurs in the middle of the Brushy Basin Member . Tidwell (1990) reported on a plant locality in Orchid Draw in the western part of DINO. A palynological (fossil pollen) assessment of the Morrison Formation, including several sites within the Monument, was conducted by Litwin et al (1998).

Recent evidence shows that dermestid beetle larvae (Coleoptera: Dermestidae) borings (Fig. 6) are preserved in dinosaur bones collected from the Carnegie Quarry (Hasiotis, et al., 1999). These trace fossils suggest subaerial exposure of the dinosaur carcasses prior to burial and represent the earliest evidence of dermestids in the paleontological record.

Recent work in the Lower Cretaceous Cedar Mountain Formation has produced some spectacular fossil specimens. One site in particular, a river-deposited bonebed, has yielded a nearly complete articulated sauropod skull, elements of a second disarticulated sauropod skull, numerous sauropod post-cranial elements, and a few isolated theropod bones. Though only a preliminary analysis of these fossils has been completed, the cranial materials appear to be some of the most complete Cretaceous sauropod specimens found in North America (A. Elder, written communication, 1999).

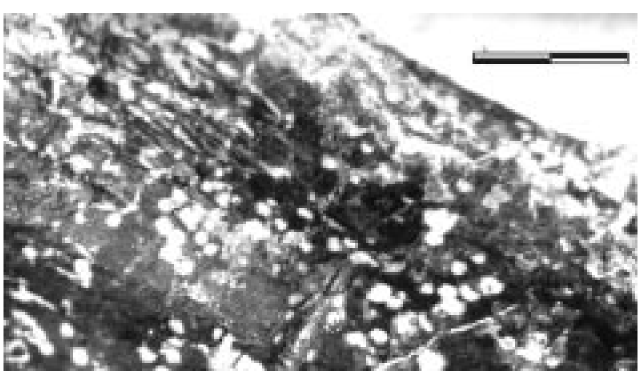


FIGURE 6. Small borings on the surface of dinosaur bone from Carnegie Quarry, Dinosaur National Monument.

The Dakota Formation of Late Early or Early Late Cretaceous age consists of shoreface and terrestrial strata deposited along the western margin of the western interior seaway. Petrified wood and fragmentary invertebrate remains have been found in the Dakota. Fish scales and bones are locally abundant in the Upper Cretaceous Mowry Shale, while bivalves, ammonites, and shark teeth are also known from this unit within DINO. The Upper Cretaceous Frontier Formation contains bivalves, gastropods, ammonites, petrified wood, and some thin coal beds. The Mancos Shale is not well exposed in the Monument, but locally this unit is very fossiliferous and preserves a high diversity of marine invertebrates. Ammonites are reported from the Mancos Shale at Ashley Creek and Brush Creek near the Monument (Kennedy and Cobban, 1991).

Sharpe (1991) reported on the Quaternary and Holocene flora in DINO that was collected to assess vegetational changes.

FLORISSANT FOSSIL BEDS NATIONAL MONUMENT

Florissant Fossil Beds National Monument (FLFO) was established by presidential proclamation on August 20, 1969 to preserve the unique fossil insects and plants found in the area. The Monument is located in central Colorado approximately 35 miles west of Colorado Springs near the town of Florissant.

The Florissant area is underlain by Precambrian Pike's Peak granite. This unit has a distinctive pink color and was formed more than one billion years ago. The massive granitic pluton was uplifted during the Late Cretaceous Laramide Orogeny (approximately 65-70 million years ago) (Meyer and Weber, 1995). Paleozoic and Mesozoic sediments were eroded away during the uplift, and a widespread erosion surface developed by Late Eocene time.

The Wall Mountain Tuff (36.6 million years old) unconformably overlies the Pike's Peak granite in the vicinity of Florissant and is exposed in isolated outcrops (Henry, et al., 1996). It is believed that the source of the Wall Mountain Tuff was the Mt. Princeton caldera (Wobus, personal communication, 2000). The Florissant Formation overlies the Wall Mountain Tuff and is composed of shales interbedded with volcaniclastic deposits (Fig. 7). Early eruptions from the Thirty-Nine Mile volcanic complex produced lahars (mudflows) that buried the giant redwoods and other trees with 13-16 feet of debris. An influx of silica-rich water saturated tree stumps and preserved them by permineralization, which accounts for the preservation of cellular structure in the stumps (Fig. 8). The lahar layer containing the petrified stumps is the lowest layer in the Florissant Formation. Subsequent volcanic eruptions, also from the Thirty-Nine Mile volcanic field, impounded the stream drainage to the south and formed ancient Lake Florissant. Plant debris and insects were trapped within the volcanic sediments that slowly washed into the lake. Diatoms flourished in the lake and contributed to the

FIGURE 7. Stratigraphy of Florissant Fossil Beds National Monument.

Stratigraphy of Florissant Fossil Beds National Monument, Colorado

Era	Period	Epoch	Formation	Member	Map Unit	Description
Cenozoic	Quaternary	Holocene	Alluvium		Qal	Brown unconsolidated humus-rich sands and gravelly sand occurring along streams.
Cenozoic	Quaternary	Holocene / Pleistocene	Colluvium		Qc	Thin gravels mantling slopes, composed of granular grus derived from the Pikes Peak Granite, rhyolitic gravel derived from the Wall Mountain Tuff, and shale, mudstone, sandstone, and silicified wood fragments derived from the Florissant Formation.
Cenozoic	Quaternary	Pleistocene	Pleistocene gravels		Qg	Thick gravels mainly composed of granular grus derived from the Pikes Peak Granite. Also includes scattered fragments of Wall Mountain Tuff and silicified wood. Vertebrate fossils rare, including a mammoth from the SW ¼, sec. 12, T. 13 S., R 71 W.
Cenozoic	Tertiary	Eocene	Florissant	Lacustrine / fluvial	Tf5	Pumice-rich white sandstones and conglomerates, structureless to locally trough crossbedded. Numerous pink pumice clasts near top. Near south entrance includes poorly sorted brown pumiceous sandstones interbedded with scattered lenticular mudstones and shales. Contains locally abundant fingernail clams, rare plant and lymnaeid snail fossils. Maximum measured thickness 22.8 m. Lacustrine at base, fluvial at top.
Cenozoic	Tertiary	Eocene	Florissant	Lacustrine	Tf4	Gray to greenish brown paper shales and blocky mudstones; interbedded with planar, thin yellow to white pumiceous sandstone beds. Near the south entrance this unit is represented by fossiliferous gray to yellowish brown sandstones interbedded with cherty stromatolites. Fossils include leaves, insects, ostracodes, fish scales, and fingernail clams. Maximum measured thickness 5.6 m in the northwest corner of the monument; unit thins to the south. Lacustrine.
Cenozoic	Tertiary	Eocene	Florissant	Volcanigenic Debris flow	Tf3	Yellowish-gray conglomerate with subangular to rounded clasts of tuff, quartz, and andesite. Locally contains blocks of andesite, pumiceous sandstones and blocky mudstone. Unit typically graded, otherwise structureless to crudely horizontally bedded. Fossils include scattered fingernail clams near top. Maximum thickness 7.9 m measured near Lodge stump (E of Scudder pit). Unit thins to the north and is not present in the northwest corner of the monument. Represents a volcanigenic debris-flow deposit.
Cenozoic	Tertiary	Eocene	Florissant	Lacustrine	Tf2	Interbedded brown paper shales, grayish brown blocky mudstones, thin yellowish pumiceous sandstones, and thin granular pumice conglomerates. Contains abundant plant fossils with less abundant insects and planorbid snails. Most of the fossil quarries in the monument occur in the this unit. Maximum thickness 9 m. Lacustrine.
Cenozoic	Tertiary	Eocene	Florissant	Fluvial / volcanigenic mudflow	Tf1	Tan to gray blocky tuffaceous mudstones interbedded with yellowish gray pumiceous sandstones and rare arkosic sandstone ribbons. The arkosic sandstones typically have abundant trough crossbedding. Fossil include stumps and logs of gymnosperms and angiosperms, scattered leaves and rare mammal bones. Bottom contact poorly exposed, with a maximum measured thickness of 10.4 m. Fluvial with a volcanigenic mudflow deposit at the top.
Cenozoic	Tertiary	Eocene	Boulder Conglomerate		Tb	Lenticular boulder conglomerate composed primarily of large rounded blocks of Pikes Peak Granite, and secondarily of gneiss and rhyolite cobbles and boulders. Rhyolite clasts are rounded to subangular and were derived from the Wall Mountain Tuff. Contains scattered silicified wood fragments. Unit is interbedded with Tf1, and rests on surface cut into the Wall Mountain Tuff and the Pikes Peak Granite. Probable equivalent of the Tallahassee Creek Conglomerate exposed south of Wrights Reservoir (Wobus and Epis, 1978). Maximum thickness about 15 m. Fluvial and debris-flow deposit.
Cenozoic	Tertiary	Eocene	Wall Mountain tuff		Twm	Rhyolitic welded tuff, brownish gray to dark gray. Contains abundant sanidine and less abundant biotite, argillized plagioclase, and magnetite. Weathers to large angular to subangular blocks. Mantles sides of the Florissant paleovalley, and is as thick as 15 m in lower exposures. Age of this tuff is 36.6 +/- 0.06 Ma based on 40Ar/39Ar dating
Precambrian	Proterozoic		Pikes Peak Granite		Pcg	Medium to coarsely crystalline reddish granite and quartz monzonite. Contains abundant perthitic microcline, quartz, and biotite. Weathers into rounded tors and boulders, and into granular grus. Age is 1041 +/- 13 Ma based on Rb/Sr isochron

Summarized from "**Surficial geologic map of Florissant Fossil Beds National Monument, Colorado**" by Evanoff, E., Brill, R.A., de Toledo, P.M., Murphey, P.C., and Cushman, R.A. Jr., 1992, . scale 1:10000. In Doi, K., and Evanoff, E., eds., 1992, The stratigraphy and paleontology of Florissant Fossil Beds National Monument: a progress report: University of Colorado Museum, 169 p.

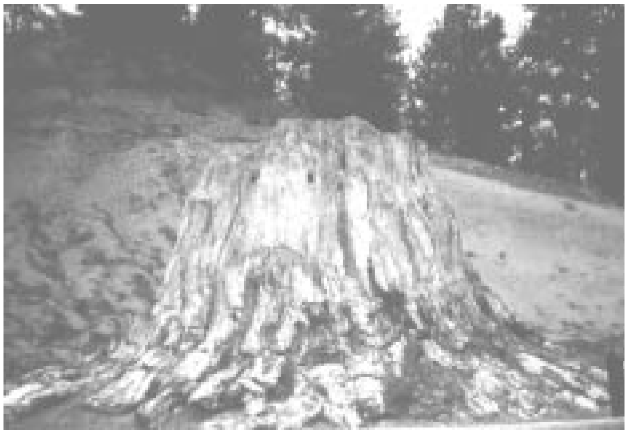


FIGURE 8. Petrified tree stump at Florissant Fossil Beds National Monument.

sedimentation processes by forming mats. These mats contributed to the preservation of the insect and plant fossils (Harding and Chart 2000). These sediments compacted over time forming fossiliferous "paper-shales".

Although the first official report of the fossil beds was published in 1874 by A.C. Peale of the Hayden Survey, the first known collection of the fossil deposits was made in 1871 by Theodore Meade (Meyer and Weber, 1995). Other research has been done by Shaler from Harvard and Cockerell from the University of Colorado To date, the Florissant Formation has yielded more that 50,000 specimens, representing approximately 140 species of plants and 1400-1500 species of insects. The world's most diverse collection of fossil butterflies has come from Florissant, representing 12 species (not including moths). The most common plants found at Florissant are *Fagopsis longifolia* and *Cedrelospermum lineatum* sp., extinct members of the Beech Family (Betulaceae) and Elm Family (Ulmaceae), respectively. The flora represents a much warmer temperate to nearly tropical climatic regime than what is found here today. Paleoclimates were calculated using floristic and physiognomic methods and different lapse rates. The Mean Annual Temperature (MAT) at Florissant during the Late Eocene has been estimated at approximately 10.7°-14°C (Meyer, 1986, 1992; Wolfe, 1992; Gregory and Chase, 1992) with an estimated paleoaltitude of 6230 - 10,500 feet (Meyer, 1992).

Figure 9. Petrified tree stump on display at Disneyland, California. The stump was collected by Walt Disney from Florissant prior to the site's establishment as a national monument.

One of the most famous of the Florissant fossils is no longer part of the park but is on display at Disneyland in California (Fig. 9). During the summer of 1956, Walt Disney visited the private Pike Petrified Forest (later to become Florissant Fossil Beds) and purchased a petrified tree stump. According to the plaque placed on the tree at Disneyland, the stump is seven feet six inches in diameter, weighs five tons and came from a tree whose original height was estimated at 200 feet (letter, Walt Disney Archives, 1999).

There are currently 59 fossil localities identified at Florissant Fossil Beds National Monument. The Monument's museum database contains historic information about each specimen, accompanied by a digital photo. A bibliographic database has also been developed by the paleontology staff at the Monument to include all publications related to the geology and paleontology of the Florissant area. A new database is being developed to compile all the most recent taxonomic designations for all plant and insect species.

GREAT SAND DUNES NATIONAL MONUMENT

Great Sand Dunes National Monument (GRSA) was established by presidential proclamation on March 17, 1932. The Monument received wilderness designation on October 20, 1976 and was upgraded to a national monument and preserve on November 22, 2000. It will become a national park as soon as a land purchase is completed. The Park is located in south central Colorado in the San Luis Valley and preserves the tallest sand dunes in North America. Individual dunes can reach 700 feet in height. The dunes cover approximately 39 square miles along the western edge of the Sangre de Cristo Range. The sand dunes were created by northeast winds transporting quartz sands and volcanic debris across this valley and depositing them at the base of the Sangre de Cristo Mountains.

The Great Sand Dunes area consists of thin layers of alluvium between layers of lava and tuff. These deposits are Miocene in age and are known as the Sante Fe Formation (Fig. 10). This unit is overlain by post-Miocene sands and clays of the Alamosa Formation (Merk, 1960). Johnson (1967) provides a more comprehensive overview of Great Sand Dunes geology. Bruce and Johnson (1991) published a geologic map that includes the Great Sand Dunes.

The Park museum collection contains some crinoid columnals and a rock specimen with the casts of three partial brachiopods. These brachiopod specimens were collected along the Mosca Pass Trail. A mammoth femur and bison phalange have also been collected in the park.

FIGURE 10. Stratigraphy of Great Sand Dunes National Park.

Stratigraphy of Great Sand Dunes National Park, Colorado

Era	Period	Epoch	Formation	Member	Map Unit	G_NOTE_TXT
Cenozoic	Quaternary	Holocene and Pleistocene	Alluvium		Qal	Sand, gravel, and clay deposited by streams. Includes Holocene stream deposits, Pleistocene glacial outwash, and, locally, colluvium; along east side of Sangre de Cristo Range, includes pediment deposits of Quaternary and possibly Tertiary age composed of deeply weathered detritus derived mostly from Precambrian and upper Paleozoic rocks.
		Holocene	Alluvial Fan Deposits		Qaf	Poorly sorted, coarse sand and gravel deposited by distributary stream systems along west side of Sangre de Cristo Range
			Eolian Sand		Qes	Surficial deposits of well-sorted sand; covered by sparse vegetation. Thin and discontinuous, interspersed with alluvial sand and clay north of Deadman Creek; dunes as high as 10 m south of Deadman Creek.
			Landslide Deposits		Ql	Deposits of angular rock debris of all sizes; typically hummocky topography
		Holocene and late Pleistocene	Rockfall Deposits		Qrf	Accumulations of talus below large outcrops
			Rock Glaciers		Qrg	Angular blocks at base of steep slopes and at floors of cirques. Lobate forms of deposits suggest formation by ice-cored flow.
	Tertiary	Pliocene and Miocene	Santa Fe Formation		Ts	Stratified sand and gravel derived mostly from Proterozoic and upper Paleozoic rocks. Overlain by deeply weathered pediment sloping away from mountains.
		Miocene	Andesite		Ta	Andesitic lahar, biotite latite, and dense hornblende-pyroxene
		Miocene?	Mafic Volcanic Rocks		Tmv	Black, vesicular, porphyritic olivine basalt; Composed of several flows probably erupted from a fissure as shown by flow foliation dipping into axis of elongate area of outcrop.
		Miocene or Oligocene	Felsic Dikes		Tf	Light-gray to white, fine-grained, felsite dikes as much as 3 m wide; porphyritic; nonfoliated.
		Miocene? or Oligocene?	Mafic Dikes		Tm	Dark-gray-green to black, aphanitic to medium-grained, holocrystalline dikes as much as 3 m wide;
Mesozoic	Jurassic	Late	Morrison Formation		Jm	interbedded gray and brown shale, gray to brown sandstone, and minor gray, fine-grained limestone; exposed in overturned syncline at Loco Hill; about 50-70 m thick
		Middle	Entrada Sandstone		Je	thin-bedded, white to tan, friable quartz sandstone; fine- to medium-grained, well-sorted, well-rounded, and frosted
Paleozoic	Permian and Pennsylvanian		Sangre de Cristo	Crestone Conglomerate Member	PPNsc	Red conglomerate, conglomeratic sandstone, and minor siltstone and shale. Exposed between Sand Creek thrust and Little Sand Creek thrust. Coarse conglomerate contains boulders and cobbles of Early Proterozoic gneiss (Xgn and Xlgn), syenite, and quartz monzonite (Xqm)
				diamictite	PPNscd	from Crestone Needle to Milwaukee Peak, in lower part of Crestone Conglomerate Member, marker bed of diamictite (d) as much as 40 m thick contains distinctive clasts of amphibolite and tourmaline pegmatite
				lower member	PPNsl	Red arkosic sandstone, conglomeratic sandstone, siltstone, and shale, arranged in fining- upward cycles, 2-40 m thick; contains crossbedding; siltstone and shale contain ripple marks, cross-lamination, and sparse mudcracks.
	Pennsylvanian	Middle	Minturn	crinoidal silty limestone	PNmcls	About 230 m below top, marker bed of crinoidal silty limestone (cls), 12-16 m thick, containing abundant crinoid columnals as much as 0.3 m long, brachiopods, sponge spicules, and bryozoans; shaly, carbonaceous, and radioactive in lower part
				oolite limestone	PNmols	About 900 m below top, marker bed of oolite limestone (ols), 4 m thick
				biohermal limestone unit	PNmbls	About 1,000 m below top, lenticular biohermal limestone units (bls), 300 m thick and extending 1,500 m along strike, containing abundant brachiopods, and other marine invertebrate fossils. Bioherms contain fusulinids of Desmoinesian age; and conodonts
	Mississippian	Lower	Leadville Limestone		MDOr	dark-gray, massive limestone, locally contains limestone breccia, 70 m thick
			Chaffee Group	Dyer Dolomite		yellow-gray, cherty dolomite, 30 m thick.
	Devonian			Parting Quartzite		gray, massive quartzite and dolomite, 15 m thick.
	Ordovician	Upper	Fremont Dolomite			dark-gray, coarsely crystalline dolomite, 70 m thick
		Middle	Harding Sandstone			pale-red, thin-bedded quartzite, 30 m thick.
		Lower	Manitou Limestone			dark-gray, fine-grained, cherty, dolomitic limestone, 60 m thick.
	Precambrian Proterozoic	Middle-Early	numerous			igneous intrusions and metamorphic rocks

FIGURE 11. Stratigraphy of Hovenweep National Monument.

Stratigraphy of Hovenweep National Monument, Colorado and Utah

Era	Period	Epoch	Formation Member			Map Unit	Description
Cenozoic	Quaternary	Holocene	Alluvium			Qa	Silt, sand, and gravel in stream valleys and flood plains; includes soil and locally some colluvial and eolian deposits.
			Eolian deposits			Qe	Reddish-brown loess on broad plains, mesas, and large benches; unconsolidated silt and sand banked against cliffs and mantling large areas of broad valleys.
			Colluvial deposits			Qc	Talus, slope wash, block rubble, rock glaciers, and in some high cirques in the San Miguel Mountains, young glacial till.
Mesozoic	Cretaceous	Upper	Mancos shale			Km	Gray to dark-gray soft fissile sparsely fossiliferous marine clay shale; a few thin distinctive calcareous sandstone and sandy clayey limestone ledges in lower 500 feet.
			Dakota sandstone			Kd	Dominantly yellowish-brown to gray quartzitic sandstone and conglomeratic sandstone in thick beds; subordinate thin lenticular beds of gray claystone, impure coal, carbonaceous papery shale, and gray friable carbonaceous sandstone; local coarse basal conglomerate. Marine near top; fluvial near base. Intertongues with Mancos Shale. A few tens of feet to 225 feet thick; averages about 100 feet thick.
		Lower	Burro Canyon			Kbc	Light-gray and light-brown fluvial quartzose sandstone and conglomerate in thick beds; lenticular greenish-gray, locally purplish, commonly non-bentonitic siltstone, shale, and mudstone; a few thin lenses of gray limestone and chert near top. Averages about 150 feet thick; thins southward to an irregular wedge edge near San Juan River south of which are only a few thin discontinuous conglomerate lenses. A few uranium deposits occur in some thick sandy conglomeratic beds and in some beds of gray shale.
	Jurassic	Upper	Morrison	Brushy Basin		Jmb	Variegated gray, pale-green, red-brown, or purple bentonitic mudstone; a few lenses of distinctive green and red chert-pebble conglomeratic sandstone, some of which contain uranium-vanadium deposits. Thickness ranges from about 150 to more than 700 feet.
				Westwater Canyon		Jmw	Mostly yellowish- and greenish-gray to pinkish-gray lenticular fine- to coarse-grained arkosic sandstone; some interbedded greenish-gray or grayish-red sandy shale and mudstone. About 180 feet thick in Bluff area; thins northeastward to a wedge edge between Blanding and Cortez.
				Recapture		Jmr	Reddish-gray, white, and brown fine- to medium-grained sandstone characterized by dark- and light-colored grains; interbedded reddish-gray siltstone and mudstone. About 200 feet thick in southwest corner of map; thins, intergrades, and intertongues northeastward with Salt Wash Member. Contains a few uranium deposits.
				Salt Wash		Jms	Pale-gray, grayish-orange, or moderate-reddish-brown fine- to medium-grained fluvial sandstone in thick discontinuous beds; interbedded greenish- and reddish-gray mudstone; thin beds of limestone locally near base. As much as 550 feet thick; more continuous sandstone beds contain numerous small and some large uranium deposits.
			San Rafael	Junction Creek Sandstone		Jj	Lateral equivalent of Bluff Sandstone. Pink or reddish-orange fine- to coarse-grained poorly sorted eolian crossbedded sandstone. Forms a rounded "slick rim." About 275 feet thick; merges northward with the upper part of Summerville Formation (a.k.a. Wanakah Formation); thins and becomes even bedded to the east and mapped with the Salt Wash Member of the Morrison Formation.
		Middle		Wanakah		Jw	25 to 100 feet thick; consists of 3 members (in descending order): marl member, greenish-gray to red-brown friable limy sandy siltstone; Bilk Creek Sandstone Member, light-colored friable fine-grained quartz sandstone in thin even beds with a distinctive red chalcedony zone at the top; Pony Express Limestone Member, dark-gray fetid bituminous thin-bedded limestone generally about 10 feet thick
				Entrada	Moab	Je	white medium-grained crossbedded or flat-bedded well sorted sandstone
					Slick Rock		white or reddish- or yellowish-orange thick massive fine- to medium-grained eolian crossbedded quartz sandstone that erodes to prominent rounded cliffs
					Dewey Bridge		reddish-brown flat-bedded locally contorted earthy siltstone and some flat-bedded white sandstone. In northeast part of map and on the southeast side of the La Plata Mountains, pale- to greenish-gray massive sandstone contains large low-grade vanadium-uranium deposits. Averages about 150 feet thick, but ranges in thickness from 70 to 440 feet.

Summarized from "*Geology, structure, and uranium deposits of the Cortez quadrangle, Colorado and Utah*" by **Haynes, D.D., Vogel, J.D., and Wyant, D.G.** 1972; scale 1:250,000 USGS Miscellaneous Investigations Series Map I-629

NOTE: squiggly lines represent unconformities (major breaks in the geologic record)

HOVENWEEP NATIONAL MONUMENT

Hovenweep National Monument (HOVE), in southwestern Colorado, was established by presidential proclamation on March 2, 1923. The site preserves a concentration of Pre-Columbian cliff dwellings, pueblos, and towers. The Upper Jurassic Morrison Formation is exposed along the south edge of Hovenweep National Monument. Locally the Burro Canyon Formation (Lower Cretaceous) and the Dakota Sandstone (Upper Cretaceous) cap the fluvial deposits of the Morrison Formation (Fig. 11).

The only report of paleontological resources from the Monument is an unidentified bone fragment found by Mike Hylland, a Utah Geological Survey geologist (M. Hayden, written communication, 1999). Although there are not many reports of fossils from within the Monument, judging from their nearby, invertebrate fossils most likely are present in HOVE (Santucci, 2000).

MESA VERDE NATIONAL PARK

Mesa Verde National Park (MEVE) was established by Congress on June 26, 1906 to preserve the famous Anasazi cliff dwellings and ruins of the southwestern Colorado high mesas. The park received wilderness designation on October 20, 1976 and World Heritage Site designation on September 6, 1978.

Mesa Verde National Park lies on a broad, flat-topped mesa with deeply cut and steep-walled canyons. The canyons are oriented north-south reflecting the regional dip of the rocks to the south. Wanek (1954 and 1959) provides a comprehensive overview of the geology of Mesa Verde National Park.

The oldest exposed geologic unit in the park is the Upper Cretaceous Mancos Shale (Fig. 12). The Dakota Sandstone directly underlies the Mancos Shale in southwest Colorado, but the Dakota is not exposed in the Park. A few fine specimens of *Tempskya* sp. were collected from the Dakota Sandstone adjacent to the park. These specimens were sent to Dr. Bill Tidwell who concluded that these specimens probably represent a new species and are younger than any other known specimens of this taxa.

The 2000-foot-thick Mancos Formation was deposited in a fluctuating inland sea, mostly far from shore. The type section of the Mancos is exposed below Point Lookout on the north side of Mesa Verde National Park. Pike (1947) originally identified five faunal zones in the 2191-foot section of Mancos Shale at the park. A detailed revision of the type section divided the formation into eight distinct faunal and lithologic units (Kirkland, et al., 1995; Leckie, et al., 1997).

The oldest member of the Mancos is the Graneros Shale Member, about 79 feet thick. The Graneros does not crop out within the park boundaries, but is found a short distance to the north. The lowest part of this bentonite-rich member has a very limited fauna, but in the upper part is an almost solid bed of small oysters, *Pycnodonte newberryi* (Stanton) (Hook and Cobban, 1977). These oysters indicate warm and shallow water conditions. Some cephalopods, gastropods, and shark teeth also occur in this oyster bed.

Above the Graneros Shale, about 45 feet of the Bridge Creek (Greenhorn) Limestone Member of the Mancos is found. The Bridge Creek Limestone crops out north of the Mesa Verde National Park capping small erosion remnants of the soft Graneros Shale. It contains a varied molluscan fauna including numerous inoceramids of the genus *Mytiloides*, and ammonites of the genera *Mammites, Watinoceras, Baculites, Kamerunoceras* and others (Leckie, et al, 1997, p. 171-173). The Bridge Creek Limestone does not contain many fossils in Mesa Verde National Park, but it has a very rich assemblage of fossils to the east near Pueblo, Colorado (Cobban and Scott, 1972). Pyritized clams are known from this unit in the park.

About 92 feet of light gray Fairport Shale overlies the Bridge Creek Limestone. The shales are soft and include many thin bentonite seams. The most common fossils are found in beds crowded with juvenile *Collignoniceras woollgari* (Mantell). No adult *C. woollgari* are found in these beds, but small oysters, fragmentary inoceramids, barnacle fragments and shark teeth occur in association with the ammonites.

Overlying the Fairport Member of the Mancos, is nearly 250 feet of dark gray, sparsely fossiliferous Blue Hill Shale. The Blue Hill does not crop out within the Mesa Verde Park boundaries and is not easily recognized topographically.

The Juana Lopez Member of the Mancos is the oldest part of the formation to crop out within the park. The widespread, highly fossiliferous Juana Lopez consists of approximately 140 feet of calcareous shale and beds of solid calcarenite. Calcarenite is composed of sand-sized grains of calcium carbonate, mostly broken fragments of mollusk shells and some recrystallized calcite. It is relatively resistant to erosion and caps many of the small buttes along the north edge of the park. The calcarenite is a dark solid rock in freshly broken specimens, but weathers a characteristic rusty color in most outcrops. The Juana Lopez is highly fossiliferous, especially in the calcarenite layers. Ammonites and bivalves are common and well preserved. The most common and stratigraphically useful ammonites are the several species of *Prionocyclus; P. macombi* Meek, *P. wyomingensis* Meek, *P. novimexicanus* (Marcou), and *P.quadratus* Cobban**;** the *Scaphites, S. warreni* Meek and Hayden, and *S. whitfieldi* Cobban, and the *Baculites, B. undulatus* d'Orbigny, *and B. yokoyami* Tokunaga and Shimizu. Four faunal zones within the Juana Lopez are based on these ammonites. Bivalves *Inoceramus dimidius* White, *Inoceramus perplexus* Whitfield, and *Nicaisolopha lugubris* (Conrad) are also useful guide fossils in this member of the Mancos Formation. Some silt, but no quartz sand, is present, as these sediments were laid down in quiet water far from a source of coarse clastics.

About 50 feet of calcareous shale named the Montezuma Valley Member overlie the Juana Lopez (Leckie, et al., 1997). Numerous prionocyclids, scaphites, baculites, bivalves, inoceramids, and oysters occur in this sequence of shales

FIGURE 12. Stratigraphy of Mesa Verde National Park.

Stratigraphy of Mesa Verde National Park, Colorado

Era	Period	Epoch	Formation	Member	Map Unit	Description
Cenozoic	Quaternary	Holocene	Alluvium		Qal	Unconsolidated sands, silts, and gravels deposited mainly in stream beds and flood plains.
			Colluvium		Qls	Unconsolidated and unsorted irregular deposits of boulders, gravel, sand, and silt derived mostly from talus and landslides.
			High level terrace gravels		Qtg	unconsolidated gravels on mesa tops in Mancos valley.
			High level terrace gravels with travertine cement		Qtgt	Poorly sorted gravel deposits (same as Qtg), locally cemented with very thick travertine.
		Pleistocene	Travertine		Qtr	calcium carbonate deposits, often associated with major joints and faults. Possibly the result of hot spring activity. Age uncertain; as of yet no age-dating research has been done on these deposits.
	Tertiary	Oligocene	Minette		Ti	Igneous plugs and dikes, light gray to almost black biotite and olivine rich lamprophyric rocks containing abundant breccias and locally rounded cobbles of basement rocks.
Mesozoic	Cretaceous	Upper	Cliff House		Kch	White to red-brown, fine to medium grained marine sandstones interbedded with sandy shales. Upper and lower units of massive sandstones separated by a unit of thinner bedded sandy shales. Thickness 200-300 feet.
			Menefee		Kme	Dark gray and brown carbonaceous non-marine shales, thin siltstones and thin coal beds in upper and lower units separated by a middle sandy unit of poorly sorted, irregular bedded sandstones, sandy shales and bentonite beds. Thickness 400-800 feet.
			Point Lookout		Kpl	White to yellow fine to medium grained marine sandstone with shaly sandstone breaks, highly cross-bedded. Thickness 360 feet.
			Mancos	Smoky Hill	Kms	A prominent oyster (Pseudoperna congesta) bench about 900 feet above base of Mancos Formation.
				Juana Lopez	Kmj	About 500 feet above base of Mancos, 140 feet of highly fossiliferous dark silty shale with numerous beds of orange weathering calcarenite and thin bentonites.
				Bridge Creek	Kmb	50 feet of light gray limestone and calcareous shale about 80 feet above Dakota / Mancos contact. (Also referred to as 'Greenhorn Member' on map.)
			Dakota sandstone		Kd	Dark brown medium to coarse grained marine sandstone.

but not in the abundance of those found in the Juana Lopez.

Nearly 300 feet of limy shales and limestone overlie the Montezuma Valley Member of the Mancos. This unit is correlated with the Smoky Hill Member of the Niobrara Formation. The Smoky Hill forms prominent benches around the north edge of the Mesa Verde. The oyster *Pseudoperna congesta* (Conrad) encrusts very large *Inoceramus (Volviceramus) grandis* (Conrad) and form compact solid beds within the Smoky Hill, which makes an easily recognized stratigraphic horizon. *Scaphites depressus* (Reeside) and *Baculites codyensis* Reeside are found in the middle part of the Smoky Hill sequence, and in the upper part are inoceramids such as *Inoceramus (Platyceramus) platinus*(Logan, *I. (Endocostea) balticus* Boehm, *I. (Magadiceramus) subquadratus* Schluter and the ammonites *Desmoscaphites bassleri (*Reeside) and *Scaphites hippocrepis* (DeKay).

The uppermost portion of the Mancos Formation consists of almost 1300 feet of sandy shale and thin shaly sandstones, previously referred to as the Transitional Zone. Leckie (1997) has named it the Cortez Member. It represents the beginning of a regressive stage of deposition and consists of shallow water, near shore deposits. Within this thick sequence fossils are sparsely scattered, and include baculites, occasional scaphites, a *Placenticeras planum* Hyatt, and rarely the crinoid *Uintacrinus*.

FIGURE 13. Stratigraphy of Rocky Mountain National Park.

Stratigraphy of Rocky Mountain National Park, Colorado

Era	Period	Epoch	Formation	Map Unit	Description
Cenozoic	Quaternary	Holocene-Pleistocene	Numerous		Man-made fill, Roaring River alluvial fan deposits, Holzwarth debris flow deposits, snow and ice, alluvium, organic rich sediment, colluvium, landslide deposits, talus, rock glacier and till deposits
		Pleistocene	Till: Pinedale age	Qp	Subangular to subrounded boulders, cobbles, and pebbles set in a sandy silt to silty sand matrix. Pinedale glaciation probably began > 35,000 years ago, and occurred in several pulses. Last major advance approached its maximum ~ 22,000 years ago, and these glaciers began to recede from their terminal moraines between 13,000-15,000 yrs. ago. Most gone by 10,000-11,000 yrs. ago (age data from Madole and Shroba, 1979, p. 128-129).
			Till: Bull Lake age	Qb	Subangular to subrounded boulders, cobbles, and pebbles in a silty sand matrix. Till of Bull Lake age may have been deposited between about 130,000-150,000 years ago (Madole and Shroba, 1979, p. 130).
			Till: pre-Bull Lake age	Qpb	Boulders and cobbles in a silty sand matrix. Age very poorly known-possibly deposited between 400,000-550,000 years ago (Madole and Shroba, 1979, p. 133).
			Gravel deposits	Qg	Stratified deposits of rounded to subrounded cobbles, pebbles, and sand of pre-Bull Lake age.
	Neogene		Diamicton	QNd	Unsorted, unstratified deposits of boulders, cobbles, and pebbles in a silty sand matrix.
	Tertiary	Lower Miocene	Troublesome	Tt	Gray and orange-gray, tuffaceous mudstone and sandstone, volcanic ash beds, and minor clayey limestone and conglomerate; several interlayered basaltic lava flows
		Oligocene	Sedimentary rocks, undivided	Ts	Small exposures of sedimentary rocks that interfinger with or underlie Oligocene volcanic deposits south of Peterson Park, west of Long Draw Reservoir, between Thunder Mountain and Iron Mountain, and northeast of Specimen Mountain on the ridge between Willow Creek and the Cache la Poudre River.
		Eocene Paleocene	Coalmont Formation	Tc	Gray to brown, fine- to medium-grained, arkosic sandstone, dark-gray carbonaceous mudstone, and conglomerate containing clasts as large as 1.5 m..
Mesozoic	Cretaceous	Upper	Pierre Shale	Kp	Interbedded silty shale and sandstone overlying dark-gray to black shale. Lower 500 m. of formation, poorly exposed north of Porphyry Peaks, contains fossils identified as *Inoceramus subcompressus* Meek and Hayden, *Didymoceras* sp., and *Baculites gilberti* Cobban (W.A. Cobban, written commun., 1974); lower formation, exposed southwest of site of Willey Lumber Camp on south side of Michigan River, contains *Baculites obtusus* Meek (O'Neill, 1976, p. 39). Adjacent to the Mount Richthofen stock, the Pierre has been thermally metamorphosed to dense, hard, medium- to dark-gray hornfels that weathers yellowish gray. O'Neill (1976, p. 39-40) correlated this hornfels at Nokhu Crags with the Terry and Hygiene Sandstone Members of the Pierre, and reported *Inoceramus barabini*, Morton from the upper and middle sections.
			Niobrara Formation	Kn	Light- to dark-gray calcareous shale.
			Benton Shale	Kb	topmost beds of fossiliferous limestone and underlying very fine grained sandstone (thickness about 12 m. total) contain fossils of Juana Lopez age (Late Cretaceous;
					middle unit is medium-gray calcareous shale (thickness about 60 m)
		Lower			lower unit is medium- to dark-gray non-calcareous shale (thickness about 46 m.).
			Dakota Formation	Kd	Light-gray to light-brown, very fine grained to fine-grained, ripple-marked, thin- to very thick bedded sandstone; locally conglomeratic; local trace fossils (tracks and burrows) in upper part; light-gray to light-brown lenticular conglomeratic sandstone and chert pebble conglomerate in lower part; thickness varies from about 25 to 75 m.
	Jurassic	Upper	Morrison Formation	Jm	Green, greenish-gray, and grayish-red silty claystone, light-gray sandstone, and a few thin, discontinuous beds of dense limestone; thickness about 90 m.
			Sundance Formation	Js	Buff very fine grained sandstone and laminated siltstone; about 40 m. thick.
		Middle			
	Triassic	Lower	Chugwater Formation	TrPc	Reddish-brown to orange-red shale, siltstone, and fine-grained sandstone; laminated to thin bedded; contains detrital mica; also Upper Permian in age
Precambrian Proterozoic		Middle	Intrusive igneous		Gabbro of the iron dike, Silver Plume granite, garnet-sillimanite granite, leucogranite, granite aplite, intrusion breccia, granite of Hagues Peak, mafic dikes, biotite-muscovite granite, quartz diorite, Boulder Creek granodiorite, trondhjemite of Thompson Canyon, pegmatite
		Early			
			Metamorphic rocks		Biotite schist, microcline-biotite-quartz-plagioclase granofels, hornblende gneiss and amphibolite, calc-silicate gneiss, biotite schist and hornblende gneiss, granitic gneiss, leucocratic gneiss.

Summarized from ***"Geologic Map of Rocky Mountain National Park and Vicinity, Colorado"*** *by William A. Braddock and James C. Cole, scale 1:50,000;*
USGS Miscellaneous Investigations Series Map I-1973
NOTE: squiggly lines represent unconformities (major breaks in the geologic record)

Overlying more than 2000 feet of the Mancos Formation is the Mesaverde consisting of three formations from the oldest to the youngest: the Point Lookout, Menefee, and Cliff House.

The Point Lookout Formation consists of a series of about 300 feet of thick sandstones deposited in shallow water and along beaches of a regressing sea. The contact with the upper Cortez Member of the Mancos is gradational and difficult to place. The Point Lookout Sandstone is a cliff-forming unit, which makes the resistant cap rock around the rim of the Mesa Verde. There are few identifiable fossils in this formation, but trace fossils are common and a large *Baculites* cf *haresi*, some broken inoceramids, and drift wood are present.

The sea drained off to the northeast, and the area became a lowland, coastal plain. Thick deposits of the Menefee Formation totaling up to 800 feet in places, were laid down in swamps, lagoons, and along broad meandering streams and include woody shales, coal, dark carbonaceous shales, and discontinuous irregular stream sands. No invertebrate or vertebrate fossils have been found, but a rich paleobotanical record is present, especially in the sandstones of the middle part of the formation. Although plant fossils are common in this unit, identification has been difficult because of problems in preservation. Paleobotanists who have been helpful in making identifications of specimens brought to them from MEVE include Jack Wolfe (USGS retired), Gary Upchurch (formerly USGS), Kirk Johnson (DMNH), Elizabeth Wheeler (NC State University), Una Smith (Yale Univ). Petrified wood is common in the sandstone units and has been identified as conifer. A few pieces of wood, along with bark and twigs, have been identified as *Auricaria.* Palms identified as *Sabal* and *Sabalites* are quite common and well preserved in the sandstones and make a thick hash of broken fronds in one layer of the Menefee. Other paleontological material includes: grass blades, a crushed stem of *Calamites*, a twig of a probable *Sequoia*, an unknown fern, a monocot, *Brachyphyllum,* and leaves from *Sycamore, Theaceae, Laurel, Camelia,* and *Ficus* trees. Kirk Johnson identified a well-preserved flower bud as probably *Paleoaster iniqueriende*, but is much smaller than any other known specimen. Una Smith (Yale University) indicated that the specimen resembles a paleoaster, but cannot refer it to a known species (Griffitts, personal communication, 2001).

The youngest Mesozoic sediments on the Mesa Verde are the marine sandstones of the Upper Cretaceous Cliff House Formation deposited in a shallow transgressive sea. The formation consists of two massive sandstone beds separated by a shaly sandstone unit. The prehistoric Puebloan cliff dwellings were constructed in alcoves in the massive sandstones. Invertebrate, vertebrate, and trace fossils are found throughout the formation (Siemers and King, 1974). The ammonite *Baculites maclearni* Landes is common within the unit and more rare are fragments of a *Placenticeras sp.* Bivalves include *Ethmocardium whitei, Cymbophora, Modiolus, Dosinopsis,* and *Inoceramus.* Several echinoids have been found and an excellent sea star, probably representing a new species and possibly a genus, was also collected.

Fossil vertebrates from the Cliff House include jaw, fins and isolated teeth from the bony fish *Enchodus*, shark teeth, amphibians, and reptiles (mosasaurs, plesiosaurs, turtles). Trace fossils including the Crustacean burrows *Ophiomorpha* are abundant throughout the sandstones. In 1934, during the construction of an addition to the Mesa Verde park museum, many excellent upper Cliff House fossils were collected.

Holocene insect fossils have been reported from a number of the Anasazi archeological sites within the park (Graham, 1965). Analysis of fossil insect assemblages indicated that the synanthropic insect population remained virtually unchanged from the Basketmaker culture through the Pueblo culture (Elias, 1997). Insect fossils were found associated with human remains, coprolites, and in food storage containers.

ROCKY MOUNTAIN NATIONAL PARK

Rocky Mountain National Park (ROMO) was established as a national park on January 26, 1915. The park was designated a Biosphere Reserve in 1976 and given wilderness designation on December 22, 1980. Rocky Mountain National Park has the highest elevation of any of the NPS areas in Colorado and includes the highest peaks of the Front Range in the Rockies. This area is sometimes referred to as the "Roof of the Rockies" as the Continental Divide crosses through Rocky Mountain National Park. The park shows extensive evidence of several different glacial episodes. Glacial features including cirques, moraines, icefields, glacial lakes, striations, and glacial debris are evident within the park.

The oldest rocks in Rocky Mountain National Park consist of Precambrian gneisses and schists dated to approximately 1.8 billion years old (Fig. 13). These metamorphic rocks have been intruded by granite batholiths. During the Tertiary, the Laramide Orogeny caused regional uplift and increased volcanic activity. Glacial activity started during the Pleistocene Epoch around 1.5 million years ago, representing the Bull Lake glaciation and the Pinedale glaciation (Wisconsinan age). The last of the Pleistocene glaciers disappeared in the park region about 7500 years ago (Harris, 1977). There are still several small active glaciers within the park boundaries.

Paleontological resources known from Rocky Mountain National Park are limited to the Pleistocene and Holocene. Although the Mancos Formation is exposed in the park, there are no documented fossil specimens reported from this unit. There are a few enigmatic specimens in the museum collection at ROMO, including several pieces of petrified wood, *Stylommatophora,* several molluscan specimens as well as other marine fossils. Additional specimens in the park collection include teeth from *Ursus americanus, Equidae* sp. and *Bovidae* sp. and ten plant fossils from the Willow Creek Pass area just outside the park boundaries. There are 35 different Holocene insects identified from the Mount Ida

Ridge Pond (Elias, 1985), with additional specimens from the Roaring River and La Poudre Pass sites that are listed in Appendix B (Elias, 1996a, 1996b). Pollen samples were also collected from these localities.

YUCCA HOUSE NATIONAL MONUMENT

Yucca House National Monument (YUHO) was proclaimed a national monument on December 19, 1919 to preserve a complex of unexcavated prehistoric Native American pueblos. The site is administered through Mesa Verde National Park and is currently not open to the public. The monument located on the west side of the broad Montezuma Valley south of McElmo Creek consists of a group of unexcavated mounds outlining kivas and room blocks originally described and sketched by W.H. Holmes during his 1875-76 field excursions (1876).

The bedrock geology at Yucca House consists of the Upper Cretaceous Mancos Formation. The Mancos Formation has been divided into eight members at the type section at Mesa Verde National Park by R.M. Leckie (Leckie, et al., 1997). However, at Yucca House only the top four members are exposed within the monument boundaries. The lower four, the Graneros shale, the Bridge Creek (Greenhorn) Limestone, and the Fairport and Blue Hills Shales crop out to the west of the monument. The older Dakota Formation crops out about 2 ½ miles north and about 2 ½ miles west of the present boundaries of Yucca House.

The oldest sedimentary rock cropping out in the monument, the Juana Lopez Member of the Mancos, is most important to Yucca House both in paleontology and archeology. The low mesas just west of the monument boundary are capped by the rusty calcarenite of the Juana Lopez Member. The gullies between the small hills cut into this member. The Juana Lopez is a highly fossiliferous unit composed of dark soft calcareous shales and hard calcarenite layers. The calcarenite is a granular, solid rock that resembles a sandstone, but is almost entirely composed of calcium carbonate. It is dark gray, almost black in fresh specimens, but weathers to a rusty brown. Solution of pieces of this calcarenite in hydrochloric acid leaves only a very small residue of fine silt and clay. The Juana Lopez represents a period of quiet deposition far from shore, with little clastic material being brought into the area. Although the calcarenite is largely composed of bioclastic debris such as broken shell material, some probably represents a chemical recrystallization of calcium carbonate derived from the molluscan shells.

Much of this part of the Montezuma Valley is underlain by the Juana Lopez Member. The dip is gentle, rarely more than 3 degrees, so that a relatively thin formation, less than 140 feet thick, crops out over a large geographic area. Most of the valley is covered with alluvium and terrace and landslide deposits, so bed rock outcrops are not common. The area has been cultivated for generations and soil covers much of the flat area. Bedrock crops out west of Yucca House Monument in the low foothills below the Ute Mountain laccoliths.

The Juana Lopez calcarenites bear a rich fauna of ammonites and bivalves. *Prionocyclus wyomingensis* Meek and *P. novimexicanus* (Marcou), *Baculites undulatus* d'Orbigny and *B. yokoyami* Tokunaga and Shimizu,. and *Scaphites warreni* Meek and Hayden and *S. whitfieldi* Cobban are common ammonites. Common bivalves include *Nicaisolophalugubris* (Conrad), *Inoceramus dimidius* White, *I. perplexus* Whitfield and various small oysters. This member is so highly fossiliferous that almost every block of calcarenite shows at least fragments of molluscs. A collection of fossils from the monument are catalogued and stored at the Mesa Verde Museum.

The paleontologic record is especially important to the archeologist because many of the building blocks visible in the rubble mounds have well-preserved fossils of the above species (Fig. 14). The closest outcrop of this fossiliferous zone is about ½ mile to the west. Where the Juana Lopez is cut by gullies, ready-made building blocks, shaped by 3-6 inch bedding planes plus vertical jointing, are found. The layer that caps the low hills is usually thinner bedded and would not make good building material. Some of the building blocks are boulders from the terrace gravels and landslide debris, but a large part is the highly fossiliferous Juana Lopez calcarenite.

Two small outcrops of the Smoky Hill Member of the Mancos are found several miles to the east of Yucca House with typical bivalves, *Pseudoperna congesta* (Conrad) encrusting *Inoceramus (Volviceramus) grandis* (Conrad), and *Inoceramus (Platyceramus) platinus* Logan.

ACKNOWLEDGEMENTS

We thank the many National Park Service employees who provided their time and expertise during the inventory of paleontological resources in the various NPS units of Colorado including: Nancy Russell and Jackson Moore (retired) from Bent's Old Fort National Historic Site; Ken Stahlnecker, Joanie Budzileni, Kelli Trujillo, and Mitzi Frank from Black Canyon of the Gunnison National Park and Curecanti National Recreation Area; J. Lofland, Pat Perrotti, William Hood, and Dave Price from Colorado National Monument; Ann El-

FIGURE 14. Fossil bivalves in the building stones at an archeological site in Yucca House National Monument.

der and Scott Madsen from Dinosaur National Monument; Herb Meyer, A. Cook, and A. Kinchloe from Florissant Fossil Beds National Monument; Andrew Valdez and Sue Judis from Great Sand Dunes National Park; George San Miguel, Jack Muller, and M. Colyer (photographer) from Mesa Verde National Park; and Bill Butler from Rocky Mountain National Park.

We extend an additional thanks to William Cobban (USGS), Wally Hansen (USGS), Jim Kirkland (Utah State Paleontologist), George Engelmann (University of Nebraska at Omaha), Mary Griffitts (retired geologist), Tony Fiorillo (Dallas Museum of Natural History), Scott Elias (University of Colorado), Jason Kenworthy (Fossil Butte National Monument), Steve Hasiotis (University of Indiana), and George Jefferson (Anza-Borrego Desert State Park) for technical information and review of this document.

Finally we would like to acknowledge our appreciation of J. Gregson, B. Heise, B. Higgins and D. McGinnis of the National Park Service, for providing the opportunity to include paleontology as part of the Geologic Assessment of the Colorado National Parks and Monuments.

REFERENCES

ANONYMOUS, 1990. Resource/Boundary evaluation for lands adjacent to Black Canyon of the Gunnison National Monument, Colorado, United States Department of the Interior, National Park Service. pp. 76.

ARMSTRONG, H.J. and A.J. KIHM, 1980. Fossil vertebrates of the Grand Junction Area, Grand River Institute, Grand Junction, CO, 230 pp.

ASH, S., 1993. Plant megafossils of the Upper Jurassic Morrison Formation, Dinosaur National Monument, Utah, *in* V.L. Santucci (editor), National Park Service Paleontological Research Abstract Volume: NPS Technical Report NPS/NRPEFO/NRTR-93/11, p. 44.

______, 1994. First occurrence of *Czekanowskia* (Gymnospermae, Czekanowskiales) in the United States: Review of Palaeobotany and Palynology, v. 81, p. 129-140.

BILBEY, S.A. and J.E. HALL, 1999. Marsh and "*Megalosaurus*" – Utah's first theropod dinosaur, *in* Gillette, D.D., (editor), Vertebrate Paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 67-69.

BRUCE, R.M. and B.R. JOHNSON, 1991. Geologic map of parts of the Zapata Ranch and Mosca Pass Quadrangles, Alamosa and Huerfano Counties, Colorado. U.S. Geological Survey Miscellaneous Field Studies Map, MF-2168.

CALLISON, G.L., 1977. Inventory of fossil vertebrates in Morrison Formation rocks on the Colorado National Monument, Colorado National Monument Association, Inc. , p. 33.

CHURE, D.J., 1987. Dinosaur National Monument: a window on the past, *in* Averett, W.R., (editor), Geology and Paleontology of the Dinosaur Triangle: Museum of Western Colorado, Grand Junction, Colorado, p. 75-77.

______, 1992. Leaping lizards, frolicking frogs, swimming salamanders, and minute mammals: the non-dinosaurs of Dinosaur National Monument: Park Science, v. 12, no. 3, p. 7.

______, 1993. The first record of ichthyosaurs from Utah: Brigham Young University Geology Studies, v. 39, p. 65-69.

______, 1994. *Koparion douglassi*, a new dinosaur from the Morrison Formation (Upper Jurassic) of Dinosaur National Monument: The oldest troodontid (Theropoda: Maniraptora): Brigham Young University Geology Studies, v. 40, p. 11-15.

______ and G.F. ENGELMANN, 1989. The fauna of the Morrison Formation in Dinosaur National Monument, *in* Flynn, J.J., (editor), Mesozoic and Cenozoic vertebrate paleontology: classic localities, contemporary approaches: 28th International Geological Congress Field Trip Guidebook T322, American Geophysical Union, Washington, D.C., p. 8-14.

______, and J.H. MADSEN, 1993. A new carnosaurian dinosaur from the Salt Wash Member of the Morrison Formation of Dinosaur National Monument, *in* V.L. Santucci, (editor), NPS Paleontological Research Abstract Volume: NPS Technical Report NPS/NRPEFO/NRTR-93/11, p. 47.

______, and J.S. MCINTOSH, 1990. Stranger in a strange land: a brief history of the paleontological operations at Dinosaur National Monument: Earth Sciences History, v. 9, no. 1, p. 34-40.

______, G.F. ENGELMANN, and S.K. MADSEN, 1989. Non-mammalian microvertebrates from the Morrison Formation (Upper Jurassic, Kimmeridgian) of Dinosaur National Monument, Utah-Colorado, USA: Journal of Vertebrate Paleontology, v. 9 (supplement to no. 3), p. 16A-17A.

______, J.H. MADSEN, and B.B. BRITT, 1993. New data on theropod dinosaurs from the late Jurassic Morrison Formation: Journal of Vertebrate Paleontology Abstracts with Program 13 (supplement to no. 3).

______, C.E. TURNER, AND F. PETERSON, 1992. An embryo of the ornithopod dinosaur Camptosaurus from the Morrison Formation (Upper Jurassic) of Dinosaur National Monument: Journal of Vertebrate Paleontology 12 (supplement to no. 3): p. 23A-24A.

COBBAN, W.A. and S.C. HOOK, 1979. *Collignoniceras woollgari woollgari* (Mantell) ammonite fauna from Upper Cretaceous of Western Interior, United States: New Mexico Bureau of Mines and Mineral Resources Memoir 37, p. 51.

______ and G.R. SCOTT, 1972. Stratigraphy and ammonite fauna of the Graneros Shale and Greenhorn Limestone near Pueblo, Colorado: U.S. Geological Survey Professional Paper 645, 108 p.

______, P.W. SKELTON, and W.J. KENNEDY, 1985. Occurrence of the rudistid *Durania cornupastoris* (Des Moulins, 1826) in the Upper Cretaceous Greenhorn Limestone in Colorado. Geological Survey Bulletin, Chapter B 1985, p. D1-D8.

DRIESE, S.G., 1982. Sedimentology, conodont distribution, and carbonate diagenesis of the Upper Morgan Formation (Middle Pennsylvanian), northern Utah and Colorado. Ph.D. Thesis, Dept. of Geology, University of Wisconsin – Madison, 280 pp.

Dubiel, R.F., 1992. Sedimentology and depositional history of the Upper Triassic Chinle Formation in the Uinta, Piceance, and Eagle Basins, northwestern Colorado and northeastern Utah. USGS, Chapter B 1787-W, p. W1-W25.

Elder, A.S., 1999. The history of Dinosaur National Monument's Douglass Quarry – the Park Service years, Gillette, D.D., editor, Vertebrate paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 71-76.

Elias, S.A., 1985. Paleoenvironmental interpretations of Holocene insect fossil assemblages from four high-altitude sites in the Front Range, Colorado, U.S.A. Arctic and Alpine Research, vol. 17(1), p. 31-48.

______, 1996a. Late Pleistocene and Holocene seasonal temperatures reconstructed from fossil beetle assemblages in the Rocky Mountains., Quaternary Research, vol. 46, p. 311-318.

______, 1996. Rocky Mountain National Park: Life in the rarified air. The Ice Age History of Rocky Mountain National Parks, 170 pp.

Emslie, S.D., 1986. Late Pleistocene vertebrates from Gunnison County, Colorado. Journal of Paleontology, 60(1), p. 170-176.

Engelmann, G.F., 1992. Paleontological survey of the Jurassic Morrison Formation in Dinosaur National Monument: Park Science, v. 12, no. 3, p. 8-9.

______, and G. Callison, 1999. *Glirodon grandis*, a new multituberculate mammal from the Upper Jurassic Morrison Formation, *in* Gillette, D.D., (editor), Vertebrate Paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 161-177.

_______ and A.R. Fiorillo, 2000. The taphonomy and paleoecology of the Upper Morrison Formation determined from a field study of fossil localities. Geo Research, vol. 6, p. 533-540.

______, D.J. Chure, and S.K. Madsen, 1989. A mammalian fauna from the Jurassic Morrison Formation of Dinosaur National Monument, Journal of Vertebrate Paleontology Abstracts with Programs, v. 9 (supplement to no. 3), p. 19A.

Evans, S.E., and D.J. Chure, 1999. Upper Jurassic lizards from the Morrison Formation of Dinosaur National Monument, Utah. *in* Gillette, D.D., (editor), Vertebrate Paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 151-159.

Fiorillo, A.R., 1996. Paleontologic resources in the Upper Jurassic Morrison Formation of Curecanti National Recreation Area and Black Canyon of the Gunnison National Monument, Colorado; Final report, p. 105-116.

______, 1999. Non-marine trace fossils from the Morrison Formation (Jurassic) of Curecanti National Recreation Area, Colorado, *in* V.L. Santucci and L. McClelland, (editors), NPS Paleontological Research Volume 4, Technical Report NPS/NRGRD/GRDTR-99/03, p. 42-46.

______ and R.L. Harris, 2000. Late Jurassic (Morrison Formation) Continental Trace Fossils from Curecanti National Recreation Area, Colorado. Park Science, v. 20, p. 28-30.

______, R.L. Harris, and C.L. May, 1996. Late Jurassic dinosaur remains from Curecanti National Recreation Area. Park Science, 16(4), p. 14-15.

______ and C.L. May, 1995. Depositional environment of the first dinosaur remains from the Morrison Formation (Upper Jurassic) of Curecanti National Recreation Area (Southwest Colorado), Geological Society of America Program with Abstracts, Rocky Mountain Section, vol. XX, p. 11.

______ and ______, 1996. Preliminary report on the taphonomy and depositional setting of a new dinosaur locality in the Morrison Formation (Brushy Basin Member) of Curecanti National Recreation Area, Colorado, The Continental Jurassic, Bulletin of the Museum of Northern Arizona, vol. 60, p. 555-561.

_______ and D.K. McCarty, 1996. Paleopedological evidence for a humid paleoenvironment in the lower part of the Bushy Basin Member, Morrison Formation, of the Curecanti National Recreation Area, Colorado, The Continental Jurassic, Bulletin of the Museum of Northern Arizona, vol. 60, p. 575-590.

Gilmore, C.W., 1924, Expedition to the Dinosaur National Monument: Smithsonian Miscellaneous Collection, v. LXXVI, p. 12-16.

______, 1925a. A nearly complete, articulated skeleton of *Camarasaurus*, a saurischian dinosaur from the Dinosaur National Monument: Memoirs of the Carnegie Museum, v. 10, p. 347-384.

______, 1925b. Osteology of ornithopodous dinosaurs from the Dinosaur National Monument, Utah. Part I. On a skeleton of *Camptosaurus medius* Marsh. Part II. On a skeleton of *Dryosaurus altus* Marsh. Part III. On a skeleton of *Laosaurus gracilis* Marsh: Memoirs of the Carnegie Museum, v. 10, p. 385-409.

______, 1926. A new aetosaurian reptile from the Morrison Formation of Utah: Annals of the Carnegie Museum, v. 15, no. 2, p. 326-342.

______, 1932. On a newly mounted skeleton of *Diplodocus* in the United States National Museum: Proceedings of the United States National Museum, Article 18, 21 pp.

______, 1936a. Osteology of *Apatosaurus* with special reference to specimens in the Carnegie Museum: Memoirs of the Carnegie Museum, v. 11, p. 175-300.

______, 1936b. The great dinosaurs of the Carnegie Museum: Section of Vertebrate Paleontology, Pamphlet no. 2, p. 14.

Graham, S.A., 1965. Entomology: An aid in archeological studies. American Antiquity Memoirs, v. 19, p. 167-174.

Gregory, K.M. and C.G. Chase, 1992. Tectonic significance of paleobotanically estimated climate and altitude of the Late Eocene erosion surface, Colorado: Geology, v. 20,

p. 581-585.

Gregson, J.D., and D.J. Chure, 2000. Geology of Dinosaur National Monument, Utah-Colorado. *in* D.A. Sprinkel, T.C. Chidsey, Jr., and P.B. Anderson, (editors), Geology of Utah's Parks and Monuments. 2000 Utah Geological Association Publication 28, p. 155-188.

Griffitts, M.O., 1990. Guide to the geology of Mesa Verde National Park. Lorraine Press, Utah, 88 p.

Harding, I.C. AND Chant, L.S., 2000. Self-sedimented diatom mats as agents of exceptional fossil preservation in the Oligocene Florissant lake beds, Colorado, United States., Geology, v. 29, no. 3, p. 195-198.

Hansen, W.R., 1967. The Lower Black Canyon of the Gunnison, National Park Magazine, July issue, p. 14-19.

______, 1971. Geologic map of the Black Canyon of the Gunnison River and vicinity, Western Colorado. United States Geological Survey, miscellaneous geologic investigations, Map I-584, 1:24,000.

______, 1981. Geologic and physiographic highlights of the Black Canyon of the Gunnison River and vicinity, Colorado, New Mexico Geological Society Guide Books, 32nd Field Conference, Western Slope Colorado, p. 145-154.

______, 1987. The Black Canyon of the Gunnison, Colorado. Geological Society of America Centennial Field Guide – Rocky Mountain Section, p. 321-324.

______, 1996. Dinosaur's restless rivers and craggy canyon walls: Vernal, Dinosaur Nature Association, 103 p.

______, P.D. Rowley, and P.E. Carrera, 1983. Geologic map of Dinosaur National Monument and vicinity, Utah and Colorado. USGS Miscellaneous Investigations Map I-1407.

Harris, A.G., and E. Tuttle, 1977. Geology of National Parks, Kendall Hunt Publishing Company, 4th edition, 652 pp.

Hasiotis, S., 1997. In search of behavior in ancient life - animals and plant trace fossils in National Parks and National Monuments in the Four Corner States. *in* Johnston, J. and McChristal, J. (eds.), Partners in Paleontology: Proceedings of the Fourth Conference of Fossil Resources, Natural Resources Report NPS/NRFLO/NPR-97/01, p. 82-84.

______ and T. Demko, 1996. Terrestrial and freshwater trace fossils, Upper Jurassic Morrison Formation, Colorado Plateau. *in* M. Morales (ed.), The Continental Jurassic. Museum of Northern Arizona Bulletin no. 60, p. 355-370.

______, A.R. Fiorillo, and R.R. Hanna, 1999. Preliminary report on borings in Jurassic dinosaur bones: Evidence for invertebrate-vertebrate interactions, *in* Gillette, D.D., (editor), Vertebrate Paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 193-200.

Henrici, A., 1992. Fossil frogs: Dinosaur National Monument: Park Science, v. 12, no. 3, p. 11.

______, 1993. The first articulated frogs from the Upper Jurassic of North America, *in* V.L. Santucci, (editor), NPS Paleontological Research Abstract Volume: NPS Technical Report NPS/NRPEFO/NRTR-93/11, p. 53.

______, 1998. A new pipoid anuran from the Late Jurassic Morrison Formation at Dinosaur National Monument: Journal of Vertebrate Paleontology, v. 18, no. 2, p. 321-332.

Henry, T.W., E. Evanoff, D. Grenard, H.W. Meyer, and J.A. Pontius, 1996. Geology of the Gold Belt Back Country Byway, south-central Colorado: GSA Fieldtrip Guidebook, p. 1-48.

Herr, R.G., 1979. Sedimentary petrology and stratigraphy of the Lodore Formation (Upper Cambrian), northeast Utah and Northwest Colorado: Salt Lake City, University of Utah, M.S. Thesis, 129 p.

______, M.D. Picard, and S.H. Evans, 1982. Age and depth of burial, Cambrian Lodore Formation, northeastern Utah and northwestern Colorado: Contributions to Geology, University of Wyoming, v. 21, no. 2, p. 115-121.

Holland, J.W., 1912. Note on the discovery of two nearly complete sauropod skeletons in Utah: Annals of the Carnegie Museum, v. 8, p. 2-3.

______, 1915. A new species of *Apatosaurus:* Annals of the Carnegie Museum. v. 10, p. 143-145.

______, 1916. Skeletons of *Diplodocus* and *Apatosaurus* in the Carnegie Museum of Natural History: Geological Society of America Bulletin, v. 38, p. 153.

______, 1924. The skull of *Diplodocus*: Memoirs of the Carnegie Museum, v. 9, p. 379-403.

Holmes, W.H., 1878. Report on the Ancient Ruins of Southwestern Colorado, examined during the summers of 1875 and 1876, *in* F.V. Hayden, 1878, Tenth Annual Report of the United States Geological and Geographical Survey of the Territories, p. 399-400, Plate XL.

Hook, S.C. and W.A. Cobban, 1977. *Pycnodonte newberryi* (Stanton) – common guide fossil in Upper Cretaceous of New Mexico: New Mexico Bureau of Mines and Mineral Resources, Annual Report 1976-1977, p. 48-54.

Hunt, A.P., M.G. Lockley, K.L. Conrad, M. Paquette and D.J. Chure, 1993. Late Triassic vertebrates from the Dinosaur National Monument area (Utah, USA) with an example of the utility of coprolites for correlation. New Mexico Museum Natural History Science Bulletin 3:197-198.

Johnson, R.B., 1967. The Great Sand Dunes of Southern Colorado. U.S. Geological Survey Professional Paper 575-C, p. 177-183.

Kennedy, W.J., and W.A. Cobban, 1991. Coniacian ammonite faunas from the United States western interior: The Paleontological Association of London, Special Papers in Paleontology, No. 45, 96 p.

Kirkland, J.I., R.M. Leckie, and W.P. Elder, 1995. A new principal reference section for the Mancos Shale (Late Cretaceous) at Mesa Verde National Park. *in* Santucci, V.L. and McClelland, L., (editors), NPS Paleontological Research Volume 2: NPS Technical Report, NPS/NRPO/NRTR-95/16, p. 77-81.

Leckie, R.M., J.I. Kirkland, and W.P. Elder, 1997. Stratigraphic framework and correlation of a principal reference section of the Mancos Shale (Upper Cretaceous), Mesa Verde, Colorado: *in* Mesozoic geology and paleontology of the Four Corners Region, New Mexico Geological Society Guidebook, 48th Field Conference, p. 163-216.

LITWIN, R., C.E. TURNER, and F.E. PETERSON, 1998. Palynological assessment of the Morrison Formation: Dinosaur National Monument (Utah and Colorado) and the Western Interior, *in* Carpenter, K.E., D.J. Chure and J.I. Kirkland, (editors), The Morrison Symposium: An Interdisciplinary Approach: Modern Geology, v. 22, nos. 1-4, p. 297-320.

LOCKLEY, M.G., R.F. FLEMMING, and K. CONRAD, 1990. First Semiannual Report: Distribution and significance of Mesozoic vertebrate trace fossils in Dinosaur National Monument. Report to the NPS, Contract Number: PX1200-0-C809: 15 pp.

______, K. CONRAD, and M. PAQUETTE, 1992a. New vertebrate track assemblages from the Late Triassic of the Dinosaur National Monument area, eastern Utah and western Colorado. Geological Society of America, Abstracts with Programs 24 (6): 24 (abstract).

______, ______, and ______, 1992b. New discoveries of fossil footprints at Dinosaur National Monument. Park Science 12(3): 4-5

______, ______, ______, and HAMBLIN, A., 1992c. Late Triassic vertebrate tracks in the Dinosaur National Monument area, *in* Wilson, J.R., (editor), Field Guide to Geologic Excursions in Utah and Adjacent Areas of Nevada, Idaho, and Wyoming: Geological Society of America, Rocky Mountain Region Section, Utah Geological Survey Miscellaneous Publication 92, p. 383-391.

LOHMAN, S.W., 1981. The geologic story of Colorado National Monument, US Geological Survey Bulletin #1508, 142 pp.

MARSH, O.C., 1871. On the geology of the eastern Uintah Mountains: American Journal of Science and Arts, Third Series, v. 1, p. 191-198.

MEAD, J.I. AND BELL, C.J., 1994, Late Pleistocene and Holocence Herpetofaunas of the Great Basin and Colorado Plateau *in* Harper, St. Clair, Thorne and Hess, (editors), Natural History of the Colorado Plateau and Great Basin, University Press of Colorado, p. 255-275.

MERK, G.P., 1960. Great sand dunes of Colorado, Guide to the Geology of Colorado, Field Guide, p. 127-129.

MEYER, H.W., 1986. An evaluation of the methods of estimating paleoaltitudes using Tertiary flora of the Rio Grande Rift vicinity, New Mexico and Colorado, 206 pp.

______, 1992. Lapse rates and other variables applied to estimating paleoaltitude from fossil floras: Palaeogeography, Palaeoclimatology, Palaeoecology, v.99, p.71-99.

_______ and L. WEBER, 1995. Florissant Fossil Beds National Monument: Preservation of an Ancient Ecosystem, Rock and Minerals, v. 70, p. 232-239.

MOORE, J.W., Jr., 1973. Bent's Old Fort, An Archeological Study. State Historical Society of Colorado. Pruett Publishing Company, 144 pp.

PEABODY, F.E., 1948. Reptile and amphibian trackways from the Lower Triassic Moenkopi Formation of Arizona and Utah: California University, Department of Geologic Sciences Bulletin, v. 27, p. 295-468.

PIKE, W.S., Jr., 1947. Intertonguing marine and nonmarine Upper Cretaceous deposits of New Mexico, Arizona, southwestern Colorado. Geological Society of America Memoir 24, p. 1-103.

SANTUCCI, V.L., 2000. A survey of the paleontological resources from the National Parks and Monuments in Utah. *in* D.A. Sprinkel, T.C. Chidsey, Jr., and P.B. Anderson, (editors), Geology of Utah's Parks and Monuments. 2000 Utah Geological Association Publication 28, p. 535-556.

_______, A.P. HUNT, and M.G. LOCKLEY, 1998. Fossil vertebrate tracks in National Park Service areas: Dakoterra, v. 5, p. 107-114.

SHARPE, S.E., 1991. Late-Pleistocene and Holocene vegetation change in Arches National Park, Grand County, Utah and Dinosaur National Monument, Moffat County, Colorado: Flagstaff, Northern Arizona University, Quaternary Studies, M.S. Thesis, 96 pp.

SIEMERS, C.T. and N.R. KING, 1974. Macroinvertebrate paleoecology of a transgressive marine sandstone, Cliff House Sandstone (Upper Cretaceous) Chaco Canyon, Northwestern New Mexico: New Mexico Geological Guidebook, 25th Field Conference, p. 267-277.

SOHN, I.G. and R.E. PECK, 1963. *Theriosynoecum wyomingense,* a possible guide ostracode to the Salt Wash Member of the Morrison Formation: U.S. Geological Survey Bulletin 1161-A, p. A1-A10.

TIDWELL, W.D., 1990. Preliminary report on the megafossil flora of the Upper Jurassic Morrison Formation: Hunteria, v. 2, no. 8, p. 1-11.

TURNER, C.E., and N.S. FISHMAN, 1991. Jurassic Lake T'oo'dichi': A large alkaline, saline lake, Morrison Formation, eastern Colorado Plateau: Geological Society of America Bulletin, v. 103, p. 538-558.

______ and F. PETERSON, 1999. Biostratigraphy of dinosaurs in the Upper Jurassic Morrison Formation of the western interior, U.S.A., *in* Gillette, D.D., (editor), Vertebrate Paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 77-114.

TRUJILLO, K., 2000. Dino Cove Paleontological Investigations, 1994-1999, Curecanti National Recreation Area.Curecanti National Park Report, 21 pp.

UNTERMAN, G.E., and B.R. UNTERMANN, 1954. Geology of Dinosaur National Monument and vicinity, Utah-Colorado. Utah Geological and Mineralogical Survey Bulletin, v. 42, 227 pp.

______ and ______, 1969. A popular guide to the geology of Dinosaur National Monument. Dinosaur Nature Association, 126 pp.

WANEK, A.A., 1954. Geologic map of the Mesa Verde Area, Montezuma County, Colorado. United States Geological Survey, oil and gas investigations, Map OM 152, 1:63,360.

___________, 1959. Geology and fuel resources of the Mesa

Verde area, Montezuma and La Plata Counties, Colorado: U.S. Geological Survey Bulletin 1072-M, p. 667-717.

WHITE, T.E., 1958. The braincase of *Camarasaurus*: Journal of Paleontology, v. 32, no. 3, p. 477-494.

______, 1964. The Dinosaur Quarry, *in* Sabatka, E.F. (editor), Guidebook to the Geology and Mineral Resources of the Uinta Basin: Intermountain Association of Petroleum Geologists, Eighth Annual Field Conference, p. 21-28.

WOLFE, J.A., 1992. Climatic, floristic, and vegetational changes near the Eocene/Oligocene boundary in North America: *in* Eocene-Oligocene Climatic and Biotic Evolution: Princeton University Press: Princeton, New Jersey, p.421-436.

YEN, T.G., and J.B. REESIDE, 1950. Molluscan fauna of the Morrison Formation: U.S. Geological Survey Professional Paper 233-B, p. 19-51.

Appendix A: List of fossils from Haystack Cave Gunnison County, Colorado. Midwest Archaeological Center, National Parks Service Radiometric dates 14, 935± 610, 12,154± 1,700 yr BP ^{14}C

Taxa:
Bufo sp *B. boreras* or *B. woodhousei*
Sceloporus undulatus
Buteo sp.
Lagopus sp.
Sialia sp.
Ochotona princeps
Lepus sp.
Sylvilagus sp.
Marmota flaviventris
Spermophilus richardsoni
Thomomys talpoides
Thomomys sp.
Peromyscus maniculatus
Microtus longicaudus
Microtus sp.
Lagurus curtatus
Mustela frenata
Taxidea taxus
Spilogale putorius
Canis latrans
Vulpes vulpes
Vulpes sp. or *Urocyon* sp.
Ursus americanus
Acinonyx trumani
Felis colcolor
Equus sp.
Odocoileus hemionus
Antilocapra americana
Ovis canadensis
Bootherium sp.
Euceratherium sp.

Appendix B: Taxonomic list of fossil insects found in Rocky Mountain NP

Class	Order	Family	Genus and Species	Mount Ida Bog	Roaring River	La Poudre Pass
Insecta						
	COLEOPTERA					
		Carabidae				
			Agonum bembidioides		X	
			Agonum sp.		X	X
			Amara cf. apricaria	X		
			Bembidion cf. trasversale		X	
			Bembidion incertum		X	X
			Bembidion striola	X		
			Bembidion spp.		X	X
			Calathus advena		X	
			Carabus taedatus agassii		X	
			Discorderus sp.		X	
			Elaphrus cf. Clairvillei			X
			Metabletus americanus		X	
			Notiophilus directus		X	X
			Patrobus septentrionis	X		X
			Pterostichus sp.		X	
			Stenelophus conjunctus		X	
			Selenophorus gagatinus		X	
			Selenophorus planipennis	X		
			Trechus sp.		X	X
			Trichocellus mannerheimi		X	
		Dytiscidae				
			Agabus inscriptus			X
			Agabus sp.	X		X
			Enochrus sp.			X
			Hydrospous occidentalis			X
			Hydrospous sp.	X		
			Hydrospous spp.			X
			Genus indet.		X	
		Hydrophilidae				
			Cercyon sp.			X
			Helophorus linearoides			X
			Helophorus sempervarisns			X
			Helephorus sp.			X
			Hydrobius sp.			X
		Staphylinidae				
			Acidota quadrata	X	X	X
			Deinopsis sp.		X	
			Eucnecosum brunnescens	X	X	
			Eucnecosum tenue	X	X	X
			Eucnecosum spp.	X	X	X
			Geodromicus sp.	X	X	X
			Gymnusa atra			X
			Hapalarea sp.	X		
			Lathrobium spp.			X
			Lordithon sp.		X	
			Microedus sp.		X	
			Micropeplus laticollis		X	
			Mycetoporus sp.		X	
			Olophrum consimile	X	X	
			Olophrum rotundicolle	X	X	X
			Olophrum spp.	X	X	X
			Orobanus sp.		X	
			Oxytelus sp.		X	
			Quedius sp.	X	X	
			Philonthus spp.		X	X
			Phlaeopterus sp		X	

Appendix B: (continued)

Insecta			
COLEOPTERA			
Staphylinidae			
Stenus (Colonus) sp.	X		X
Stenus dissentiens	X		X
Stenus immarginatus or formicetorum		X	
Stenus leviceps		X	
Stenus spp.			X
Tachinus elongatus	X		
Tachinus frigidus		X	
Tachinus sp.		X	
Tachyporus sp.	X		
Unamis sp.		X	
Xantholinus sp.		X	
Genus indet.	X		
Histeridae			
Genus indet.		X	
Byrrhidae			
Genus indet.		X	
Elmidae			
Genus indet.		X	X
Elateridae			
Genus indet.		X	X
Cantharidae			
Podabrus sp		X	
Anobiidae			
Genus indet.		X	
Bostrichidae			
Stephanopachys sobrinus		X	
Scarabaedidae			
Aegialia lacustris		X	X
Aphodius sp.	X	X	X
Lathridiidae			
Genus indet.	X		
Nitidulidae			
cf.Epurea sp.		X	
Genus indet.			
Cucujidae			
Laemophloeus sp.	X		
Mycetophagidae			
Genus indet.		X	
Cerambycidae			
Genus indet.		X	
Chrysomelidae			
Altica spp.	X	X	X
Oedionbchis sp.		X	
Plateumaris flavipes	X		
Genus indet.	X		X
Curculionidae			
Apion sp.		X	X
Magdalis hispoides	X		
Rhynocolus marcops		X	
Genus indet.			X
Scolytidae			
Dendroctonus cf. brevicomis	X		
Dendroctonus rufipennis		X	X
Dendroctonus sp.	X		
Dryocoetes affaber	X	X	
Dryocoetes autographus		X	
Dryocoetes sp.		X	
Polygraphus rufipennis	X	X	X

Appendix B: (continued)

Insecta			
COLEOPTERA			
Phloeotribus lecontei		X	X
Pityokteines minutus	X		
Pityophthorus spp.		X	X
Scolytus piceae		X	
Genus indet	X		X
HETEROPTERA			
Lygaeidae	X		X
Genus indet			
TRICHOPTEREA			
Hydropsychidae			
Arctopsyche sp.		X	
Limnephilidae			
cf. Asynarchus sp.	X		
cf. Clistoronia sp.		X	
Dicosmoecuss sp.		X	
cf. Limnephilus sp.	X		
Genus indet	X	X	X
Rhyacophilidae			
Himalopsyche sp.		X	
Rhyacophila sp.		X	
HYMENOPTERA			
Formicidae			
Camponotus herculeanus		X	
Formica rufa cf. marcida		X	X
Leptothorax sp.	X	X	
Myrmica incompleta			X
Myrmica (incompleta) sp.		X	
Hymenoptera parasitica			
Genus indet	X		
ARACHNIDA			
Aranaeae			
Genus indet	X		
ARANEIDA			
Genus indet		X	X
ACARI			
Oribatidae			
Genus indet	X	X	X
CLADOCERA			
Daphniidae			
Daphnia spp.	X		

VERTEBRATE PALEONTOLOGICAL RESOURCES ON FEDERAL LANDS: MANAGEMENT PRINCIPLES; PROPER STEWARDSHIP; AND PUBLIC OPINION

TED J. VLAMIS
Save America's Fossils for Everyone, 6 Brookfield Rd. Wichita, KS 67206

ABSTRACT—Controversy over the proper use of paleontological resources on America's federal lands has engulfed paleontologists during the past several years. The Society of Vertebrate Paleontology (SVP) adopted a Statement of Ethics, part of which addressed this issue. SVP subsequently collaborated with the Paleontological Society (PS) to develop the joint statement "Paleontological Resources on US Public Lands". Ultimately the debate became contentious enough that The United States Senate requested the Department of the Interior (DOI) to prepare the report "Fossils on Federal and Indian Lands".

A survey of public attitudes analyzed the responses of US adults to the proper stewardship of a fossil. The initial part of the survey asked the respondents a series of questions in which they were asked to assume they had found the fossil on their land. Subsequently, they were asked the same questions, but were asked to assume they had found the fossil on public land. The study also analyzed responses towards more general questions pertaining to the stewardship of fossils and their sale.

The results of this study demonstrate that the vast majority of the American public agree on several basic principles which are consistent with those articulated in the DOI study, the SVP Ethics Statement, and the SVP-PS Joint Statement. These include the following: That scientifically significant fossils should belong to the public; that fossils should be collected by qualified personnel; that vertebrate fossils found on public lands should be protected; and that fossils found on public lands should not be sold.

America's leading paleontological societies, the federal agencies responsible for managing paleontological resources on publicly owned, federally managed lands, and the general public are all in agreement on how these resources should be managed. Public policy should reflect this consensus, and these resources should be managed in such a way as to maximize their scientific and educational value. Vertebrate fossils found on publicly owned, federally managed lands should be collected only by qualified personnel, and should remain in the public trust.

INTRODUCTION

Heightened public interest in paleontology has brought with it an increased interest in private own ership of fossils and the development of a larger commercial market to satisfy this demand. The growing commercial market and its impact on the paleontological community has forced paleontologists to grapple with a number of ethical implications.

CONSENSUS EMERGES IN THE PALEONTOLOGICAL COMMUNITY

Because of the scarcity of vertebrate fossils, and because fossil vertebrates such as dinosaurs are especially interesting to the general public, the debate over how to deal with the ethical implications arising from the growing commercial market provoked intense debate within the Society of Vertebrate Paleontology (SVP) in the 1990s. The debate led the SVP to add a Statement of Ethics to its Bylaws. All new members are required to agree to adhere to the Ethics Statement (SVP, 1994).

The SVP Ethics Statement contains several principles that are particularly noteworthy for their public policy implications. It begins by recognizing that vertebrate fossils are usually unique or rare, and that they are part of our natural heritage. The Ethics Statement assigns to vertebrate paleontologists the responsibility of ensuring that pertinent detailed contextual data are recorded when vertebrate fossils are collected and notes that collection and preparation should be done by properly trained personnel. The importance of proper curation and the assurance of access for future researchers are recognized by the Ethics Statement's provision that scientifically significant vertebrate specimens should be curated and accessioned in institutions charged in perpetuity with conserving fossil vertebrates for scientific study and education. The Ethics Statement further recognizes the responsibility of paleontologists to expeditiously disseminate information to other paleontologists and to the general public. Perhaps the most important part of the SVP Ethics Statement from a public policy perspective is the conclusion that "The barter, sale, or purchase of scientifically significant vertebrate fossils is not condoned unless it brings them into, or keeps them within, a public trust" (SVP, 1994).

The Ethics Statement has been overwhelmingly supported by the SVP membership, and has been used to guide society policy. The strength of member support for the Ethics Statement was evident when a resolution of the SVP Executive Committee expressing concern over an on-line auction of fossils because it contradicted the SVP Ethics Statement was endorsed by all but one of the approximately 200 SVP members attending the SVP Annual Meeting in 1999 (SVP, 2000).

In order to ensure that SVP's public policy recommendations and initiatives regarding fossils on s were also reflective of the wider paleontological community, SVP initiated a dialogue with the Paleontological Society. This dialogue culminated in 1999 when the two societies issued the joint position statement Paleontological Resources on U.S. Public Lands. The PS-SVP joint statement advocates public policy which, like the SVP Ethics Statement, recognizes that fossils are part of our scientific and natural heritage. It goes on to find that fossils on public lands belong to all the people of the United States and that, as such, they need special protection, and should not be collected for commercial purposes. The joint statement concludes that the two societies strongly support actions which "protect fossils on public lands as finite natural resources; encourage responsible stewardship of fossils for educational, recreational, and scientific purposes; promote legitimate access to, and responsible enjoyment of, paleontological resources on public lands by the public and amateur paleontologists for personal use, and by the professional paleontological community, including professional paleontologists from outside the U.S.; and bring fossils from public lands into public institutions where they are available for purposes of education and scientific research" (PS and SVP, 1999).

INTEREST SPREADS TO CONGRESS

Interest in how paleontological resources on s ought to be managed has not been confined to the paleontological community. Sen. Larry Pressler introduced S. 1569 in 1983 in an attempt to open publicly owned, federally managed lands for commercial collecting (S. 1569, 1983). S. 3107, introduced by Sen. Max Baucus in 1992, would have protected vertebrate fossils on publicly owned, federally managed lands in a manner similar to laws that protect archeological remains (S. 3107, 1992). H.R. 2943, introduced by Rep. Tim Johnson in 1996, would have allowed commercial collecting on publicly owned, federally managed lands (H.R. 2943, 1996).

THE AGENCIES RECOMMEND A UNIFORM POLICY FOR VERTEBRATE FOSSILS

In 1998, the US Senate requested that the Secretary of the Department of the Interior (DOI) prepare a study on how fossils on federal lands ought to be managed. In addition to all relevant DOI agencies, input into the report was received from the Forest Service and the Smithsonian Institution. In May of 2000, following a public meeting, and after receiving comments solicited in two comment periods, the DOI issued the report "Fossils on Federal and Indian Lands" (Babbitt, 2000). This report formulated the following seven basic principles and ensuing recommendations for the management of this valuable scientific and educational resource.

PRINCIPLE 1:
Fossils on Federal Lands are a Part of America's Heritage

Recommendation: Future actions should reaffirm the use of federal fossils for their scientific, educational, and where appropriate, recreational values.

PRINCIPLE 2:
Most Vertebrate Fossils Are Rare

Recommendation: Future actions should reaffirm the restriction of vertebrate fossil collection to qualified personnel, with the fossils remaining in federal ownership in perpetuity.

PRINCIPLE 3:
Some Invertebrate and Plant Fossils are Rare

Recommendation: Future actions should reaffirm mission-specific agency approaches to the management of plant and invertebrate fossils.

PRINCIPLE 4:
Penalties for Fossil Theft Should be Strengthened

Recommendation: Future actions should penalize the theft of fossils from federal lands in a way that maximizes the effectiveness of prosecutions and deters future thefts. Penalties should take into account, among other factors, the value of fossils themselves, as well as any damage resulting from their illegal collection. Future program strategies should emphasize education of federal managers, prosecutors, law enforcement personnel and the judiciary regarding the value of fossils and the techniques for the appropriate protection of fossil resources.

PRINCIPLE 5:
Effective Stewardship Requires Accurate Information

Recommendation: Future actions should acknowledge the need for gathering and analyzing information about where fossils occur, in particular the critical role of inventory in the effective management of fossil resources. Increased emphasis on fossil inventory should take into consideration, where possible, regional approaches across agency lines, using modern technology such as Geographic Information Systems (GIS). Such work could also address specific issues, such as the impact of erosion on the loss of resources.

PRINCIPLE 6:
Federal Fossil Collections Should be Preserved and Available for Research and Public Education

Recommendation: Future actions should affirm the importance of curating scientifically valuable fossils as federal property, often in partnership with non-federal institutions. Future program approaches should emphasize the use of modern technology to improve curation and access, as well as the sharing of information between and among federal agencies and other institutions.

Principle 7:
Federal Fossil Management Should Emphasize Opportunities for Public Involvement

Recommendation: Future actions should include an emphasis on public education and participation in the stewardship of fossil resources. Future program approaches should emphasize the use of technology to increase public education and awareness of the importance and benefit of fossil resources." (Babbitt, 2000 pp. 8-10).

The DOI report also documented the urgent need for better protection of fossils found on federal lands. "In a study commissioned by the Forest Service, it was found that almost one-third of the paleontological sites surveyed in the Oglala National Grassland showed evidence of unauthorized collecting. In 1999, the NPS conducted a Servicewide survey identifying 721 documented incidents of paleontological resource theft or vandalism, many involving multiple specimens, in the national parks between 1995 and 1998. The NPS and the BLM can issue citations under their regulations, but the fine imposed is usually no more than $100". (Babbitt, 2000 p. 28)

THE AGENCIES AND THE PALEONTOLOGICAL COMMUNITY AGREE

It is clear that there is substantial congruity between the principles and recommendations formulated by the DOI and the principles embraced by the paleontological community as set forth in the PS-SVP joint statement and the SVP Ethics Statement.

Principle 1 echoes similar concepts found in both the SVP Ethics Statement and the PS-SVP joint statement. All three documents state that fossils are part of our natural heritage. The DOI recommendation that fossils on federal lands be managed for their scientific, educational, and, where appropriate, recreational values is also stated clearly in the PS-SVP Joint Statement.

Likewise, Principle 2, that most vertebrate fossils are rare, is also clearly stated in both the SVP Ethics Statement and the PS-SVP joint statement. The ensuing recommendation, that collection of vertebrate fossils be restricted to qualified personnel, and that these fossils remain in the public trust, is also consistent with both the SVP Ethics Statement and the PS-SVP joint statement.

Principle 3, that many invertebrate and plant fossils are common, is not addressed in the SVP Ethics Statement as it does not pertain to vertebrate fossils; however, this principle is elucidated in the PS-SVP joint statement. The recommendation that invertebrate and plant fossils be managed on a mission-specific basis is in accord with the PS-SVP joint statement.

Because Principle 4, that penalties for fossil theft should be strengthened, reflects an evaluation of whether current penalties act as a sufficient deterrent to crime, it is outside the scope of the SVP Ethics Statement and the PS-SVP joint statement. It is, however, logical to assume that both the SVP and the PS would want to ensure adherence with any laws designed to proscribe actions contradicting the other principles embraced by those societies.

Principle 5, that effective stewardship requires accurate information, is an important part of the SVP Ethics Statement, and explanations of it by SVP members and officers have elaborated on this in greater detail (Badgley and Vlamis, 1997; Vlamis, Flynn, and Stucky, 2000). It is not addressed in the PS-SVP joint statement.

Principle 6, that federal fossil collections should be preserved and available for research and public education, is an important part of both the SVP Ethics Statement and the PS-SVP joint statement. The resulting recommendation that scientifically significant fossils be curated as federal property is in line with the statement in the SVP Ethics Statement that these should be curated and accessioned in accredited museums, universities, colleges, and other educational institutions and with the statement in the PS-SVP joint statement that supports actions that bring fossils from public lands into public institutions.

Principle 7, that federal fossil management should emphasize opportunities for public involvement, including that of amateur paleontologists, is embraced in the PS-SVP joint statement. The resultant recommendation that emphasizes the importance of public education is recognized in the SVP Ethics Statement that acknowledges the responsibilities of vertebrate paleontologists to public education.

MAJORITY OPINIONS OF THE GENERAL PUBLIC ARE IN CONGRUENCE

The fact that consensus as to how fossils on public lands ought to be managed exists between America's two foremost paleontological societies and the federal agencies responsible for managing the majority of fossil-bearing federal lands is significant. On matters of public policy pertaining to public assets, however, it is vitally important to consider the opinions of the public.

It is significant to note that the overwhelming majority of public comments received by DOI in the public meeting and the two comment periods that were part of the report preparation process agreed that fossils on federal lands should not be available for commercial collection. Likewise, the majority of the public agreed that the restriction of vertebrate fossil collection to qualified personnel should continue (Babbitt, 2000 p. 27).

That this consensus is shared by an overwhelming majority of the general population of the American people is further demonstrated by a survey of American public opinion conducted by Mktg, Inc., a market research firm that has conducted over 10,000 studies since its founding in 1979. This telephone survey of 300 American adults analyzed people's responses both to a hypothetical situation involving the discovery of a fossil, and to a series of more general questions pertaining to fossils. A random calling program was utilized which gave every telephone in the US the same probability of being called. The survey results have an accuracy rate of +/- 7%.

RESULTS OF PUBLIC SURVEY

The following hypothetical situation was described to survey participants, and they were asked to answer a series of questions. The order of the questions was randomly varied in order to avoid skewing of the results by the order of the questions.

"Imagine that you have inherited a large ranch out West. On a visit to your ranch you discover the fossil bones of an animal. At first you think that they are the bones of a cow that died in recent years. However, at closer inspection, you find that the bones are stone, the skull is strange looking, and the backbone looks different from anything you've see. Pieces of bone are washing out of a rock ledge; they are falling apart, and appear very fragile. You recall that someone told you that the fossil bones of ancient creatures are sometimes found in the area. Remember you now own the ranch."

The respondents were subsequently asked the same questions, but asked to address the same fossil being found on public land by modifying the scenario as follows.

"After your discovery you obtain a detailed survey of your property, you find out that you had actually wandered off of your property and into Public Property part of a National Grasslands, a Federal Wilderness area or a National Park. The fossil is not on your lands but rather on these Public Lands."

A FOSSIL FOUND ON PUBLIC LAND SHOULD BELONG TO THE PUBLIC

Figure 1 examines the respondents' attitude to a series of four different questions that probe their opinion regarding the proper custody of the hypothetical fossil when found on public land. 86.6 percent agree with the statement that "The fossil is part of our heritage, it belongs to everyone in the United States", 80.0 percent with the statement that "There should be a law against my selling the fossil", 81.0 percent with the statement that "There should be a law against my taking the fossil out of the United States", and 81.0 percent disagree with the statement that "The fossil is mine, finders keepers". The consistency of responses when asked in a variety of different ways is striking. Each time over 80 percent of the responses embrace DOI Principle #1 and are also consistent with the SVP-PS Joint Statement and with the SVP Ethics Statement.

NB: The percentages for "agree" and "disagree" are reversed for the second question on Figure 1 to allow for an easier comparison of similar positions when a different question is asked. In all cases the crosshatched bar represents those believing that a fossil found on public land should belong to the public.

MORE GENERAL QUESTIONS ELICITE A SIMILAR RESPONSE

Figure 2 shows the respondents' attitudes toward the proper custody of fossils by asking more general questions about fossils found both on public and on private land. The proportion of respondents believing that a fossil found on public land should belong to the public is again approximately 80 percent as found in the scenario-based questions reviewed in Figure 1. 80.3 percent agree that "Fossils found on public lands should be restricted. It should be illegal to collect them, to sell them, to destroy them, to export them out of the United States", and 75.7 percent agree that "There should be a law to stop people from collecting fossils on federally managed public lands". The fact that the proportion of respondents taking the position that a fossil found on public land should belong to the public is approximately the same regardless of which of four question are asked in the context of a specific scenario, or is in response to a general question, demonstrates that these results are not due to the wording of the question.

Support is not quite as high for arguing that fossils found on private land should belong to the public as the proportion of support drops to 64.0 percent who demonstrate their belief that fossils found on private land should also be held in the public trust by agreeing with the statement that "All fossils found in the United States, whether found on private or public lands, should be the property of public institutions like museums or universities".

THE VALUE OF FOSSILS IS IN THEIR CONTRIBUTION TO SCIENCE AND EDUCATION; EXPERTISE IS NEEDED TO EXTRACT THIS CONTRIBUTION

Figure 3 examines respondents' agreement with a series of statements when the hypothetical fossil is found on public land. It demonstrates that over 90 percent of the respondents recognize that the value of fossils lies in their contribution to science; and that expertise is needed to extract this information. 90.3 percent agree that "The fossil could be of scientific importance, I should report it to appropriate scientific authorities", and 90.7 percent agree that "The fossil could be of scientific importance, if they want it I should allow a museum or university to collect it". A significant, but smaller majority of 70.7 percent voice a desire to enforce this by law. They do so by agreeing with the statement that "There should be a law prohibiting my taking the fossil out of the ground". These overwhelming majorities would be expected to agree with the recommendation under DOI Principle #1 and with the PS and SVP that fossils should be used for educational and scientific purposes.

THE SAME REASONING PROCESS APPLIES ON A GENERAL BASIS; SCIENCE SHOULD BE SHARED

Figure 4 demonstrates that when asked more general questions the respondents apply similar reasoning, i.e., the value of fossils lies in their contribution to science; and that expertise is needed to extract this information. 89.7 percent agree with the statement that "If someone finds a fossil of a dinosaur they should not remove it unless they obtain the aid of professionals/scientists". In doing so, they implicitly endorse the recommendations of DOI Principle #2, and endorse the positions held by the PS and the SVP. A smaller but nevertheless substantial majority recognizes the importance of public education as outlined in DOI Principle #6. This is evidenced by the disagreement of 62.7 percent with the statement that "If someone finds a fossil of a dinosaur and wants to keep it in their basement that's fine with me". They would be expected to welcome the responsibility to public dissemination and education found in the SVP Ethics Statement.

NB: The percentages for "agree" and "disagree" are reversed for the second question in Figure 4 to allow for an easier comparison of similar positions when a different question is asked. In both cases the crosshatched bar represents answers that are consistent with the value of a fossil being in its contribution to science.

VERTEBRATE FOSSILS FOUND ON PUBLIC LANDS SHOULD BE PROTECTED

Figure 5 demonstrates that over 85 percent of the public support the protection of vertebrate fossils on public lands. 85.3 percent agree that "Fossils of animals with backbones are part of our national heritage and should be protected in much the same way that archeological remains (human artifacts) are now protected"; and, 88.0 percent agree that "If laws are created to restrict the collection of fossils on public lands, the only people who should be allowed to collect them are people with appropriate skills for doing so and with a permit for that purpose. All the fossils that they find should go into museums and universities prepared to protect them". These positions are consistent with DOI Principles #1, #2, and #6, and are key elements of both the SVP Ethics Statement and the PS-SVP Joint Position Statement.

DIFFERENTIATION BETWEEN WHEN A FOSSIL IS FOUND ON PUBLIC OR ON PRIVATE LAND

Figure 6 contrasts the responses to the ownership questions explored in Figure 1 depending upon whether the hypothetical find is on public or on private land. Two things stand out when looking at these data. First is a consistent diminution of support for public custody when the discovery is on private land versus when it is on public land. The 86.6 percent who agree that "The fossil is part of our heritage, it belongs to everyone in the United States" when the fossil is found on public land diminishes to 68.0 percent who agree with that same statement when the fossil is found on private land. The 80.0 percent who agree that "There should be a law against my selling the fossil" diminishes to 36.6 percent who agree with the same statement assuming the fossil is found on private land. The 81.0 percent who agree that "There should be a law against my taking the fossil out of the United States" diminishes to 57.0 percent when the fossil is assumed to be found on private land. And the 81.0 percent who disagree with the statement that "The fossil is mine, finders keepers" diminishes to 46.0 percent who disagree with the same statement assuming the fossil is found on private land.

While the percentage of those advocating public custody does not vary significantly in response to different questions for a hypothetical fossil found on public land (as discussed in the commentary on the Figure 1); significant variances are found in the responses to different questions when these pertain to custody of the same fossil found on private land. The proportions of respondents adopting a position that the fossil found on public land should belong to the public when asked four different questions are 86.6, 80.0, 81.0, and 81.0 percent. In contrast the proportions of respondents adopting this attitude towards a fossil found on private land vary widely in responding to specific statements. These percentages are 68.0, 36.6, 57.0, and 46.0 percent for the four different questions. Perhaps this is because the issue on public lands calls for a relatively straightforward determination of custody rights as applied to a public resource, in contrast to the issue on private land which requires the respondent to weigh potentially conflicting principles of property rights and the public good. Faced with a more complex decisionmaking process, people may be more sensitive to subtle changes in wording.

NB: The percentages for "agree" and "disagree" are reversed for the second question on Figure 6 to allow for an easier comparison of similar positions when a different question is asked. In all cases the crosshatched bar represents those believing that a fossil found on public land should belong to the public.

LESS DIFFERENTIATION IN ATTITUDES TOWARD THE NEED FOR SCIENTIFIC STUDY IS FOUND BETWEEN PUBLIC LAND FOSSILS AND PRIVATE LAND FOSSILS

Figure 7 builds upon the propositions examined in Figure 3 by contrasting respondents' attitudes toward the same proposition depending on whether the hypothetical fossil is assumed to be found on public or private land. It shows that the percentage who recognize that the value of the fossil is in its contribution to science (as explored in Figure 3), and thus would be expected to agree with the recommendations of DOI Principles #2 and #6, does not differ significantly as a result of the fossil being found on private instead of public land. The same percentage of 90.3 percent agree that "The fossil could be of scientific importance, I should report it to appropriate scientific authorities" regardless of whether the fossil is assumed to be found on public or private land. The 90.7 percent who agree that "The fossil could be of scientific importance, if they want it I should allow a museum or university to collect it" drops only to 83.7 percent assuming the fossil to be found on private land. The percentage does drop significantly when it involves the prohibition of excavations by untrained people on private land. The 70.7 percent who agree that "There should be a law prohibiting my taking the fossil out of the ground" when the fossil is found on public land drops to 37.3 percent if the fossil is assumed to be found on private land.

ATTITUDES TOWARD SALES OF FOSSILS

Attitudes of the respondents toward the sale of fossils are explored in Figure 8. The data demonstrate that attitudes are split down the middle toward sales of fossils in general as 49.3 percent agree that "It's okay with me for someone to buy and sell fossils" Further qualification of the significance of the fossils being sold leads to 65.3 percent condoning sales of common fossils by agreeing that "It's okay with me for someone to buy and sell common fossils", but only 34.0 percent condoning sales of scientifically significant fossils by agreeing that "It's okay with me for someone to buy and sell rare fossils, perhaps scientifically significant ones". Because they disagree with the preceding statement, 62.1 percent of the public would be expected to agree with the concluding paragraph of the SVP Ethics Statement which states that "The barter, sale, or purchase of scientifically significant vertebrate fossils is not condoned unless it brings them into, or keeps them within, a public trust".

ATTITUDES TOWARD FOSSIL SALES VARY DEPENDING UPON WHETHER THE FOSSIL IS FOUND ON PUBLIC OR PRIVATE LAND

In Figure 9 it can be seen that over 80.0 percent of the respondents are opposed to the sale of fossils found on public lands by their agreement with the statement that "There should be a law against my selling the fossil". This attitude is consistent with long-standing opinion of the SVP (Badgley and Vlamis, 1997; Vlamis, Flynn, and Stucky, 2000), with the PS-SVP Joint Position Statement, and with long-standing DOI practices (DOI, 2000). This percentage drops to 36.6 percent when the fossil is assumed to be found on private land.

Once again, responses to issues requiring the respondent to balance property rights with the pubic good show greater variation depending on the wording of specific similar questions as 46.0 percent agree that "Fossils found on private land should be legally available for sale", whereas only 38.0 percent agree that "This is the United States, we should encourage free enterprise. A law restricting the selling of fossils collected on private lands is wrong".

NB: The percentages for "agree" and "disagree" are reversed for the first and second questions in Figure 9 to allow for an easier comparison of similar positions when a different question is asked. In all cases the crosshatched bar represents those opposed to commercial sale of fossils.

SUMMARY OF PUBLIC OPINION

The following summarizes the public's opinions expressed in the data of Figures 1-9:

- Over 80 percent believe that scientifically valuable fossils should belong to the public.
- The primary value of fossils is in the information they can provide. For this reason 90 percent feel they ought to be collected by qualified personnel.
- Over 70 percent believe this should be a legal requirement for fossils on public lands.
- Over 85 percent believe vertebrate fossils on federal public lands should be protected.
- Over 80 percent believe fossils found on public lands should not be sold. This drops to 36-45 percent for fossils found on private lands.
- Over 60% believe that scientifically significant fossils should not be sold.

CONCLUSION

America's leading paleontological societies, the federal agencies responsible for managing paleontological resources on publicly owned, federally managed lands, and the general public are all in agreement on how these resources should be managed. Public policy should reflect this consensus, and these resources should be managed in such a way as to maximize their scientific and educational value. Vertebrate

Figure 1

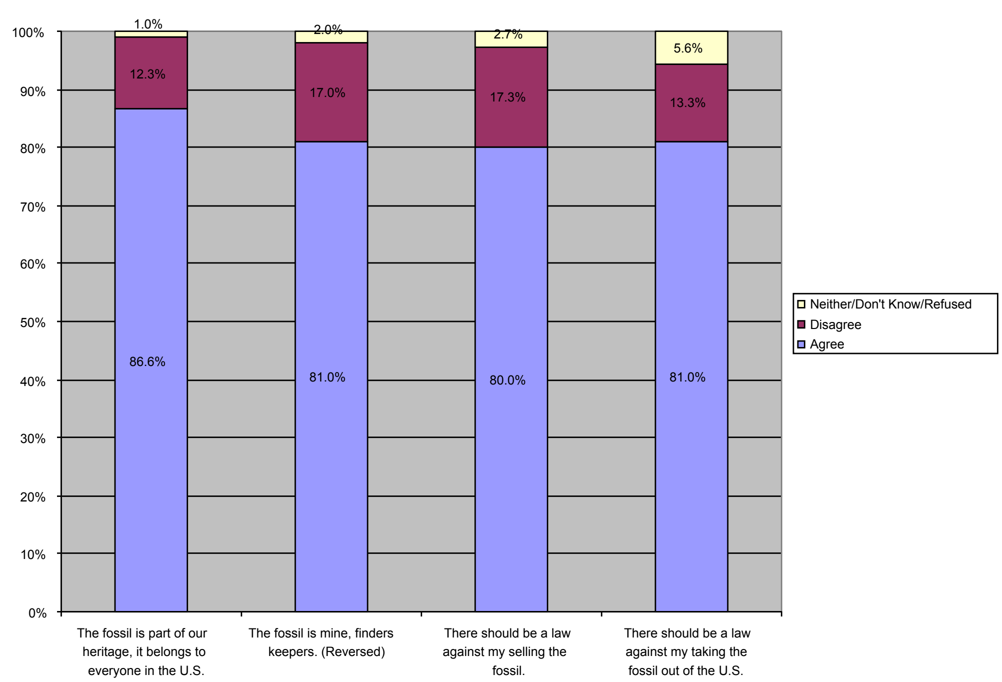


Figure 2

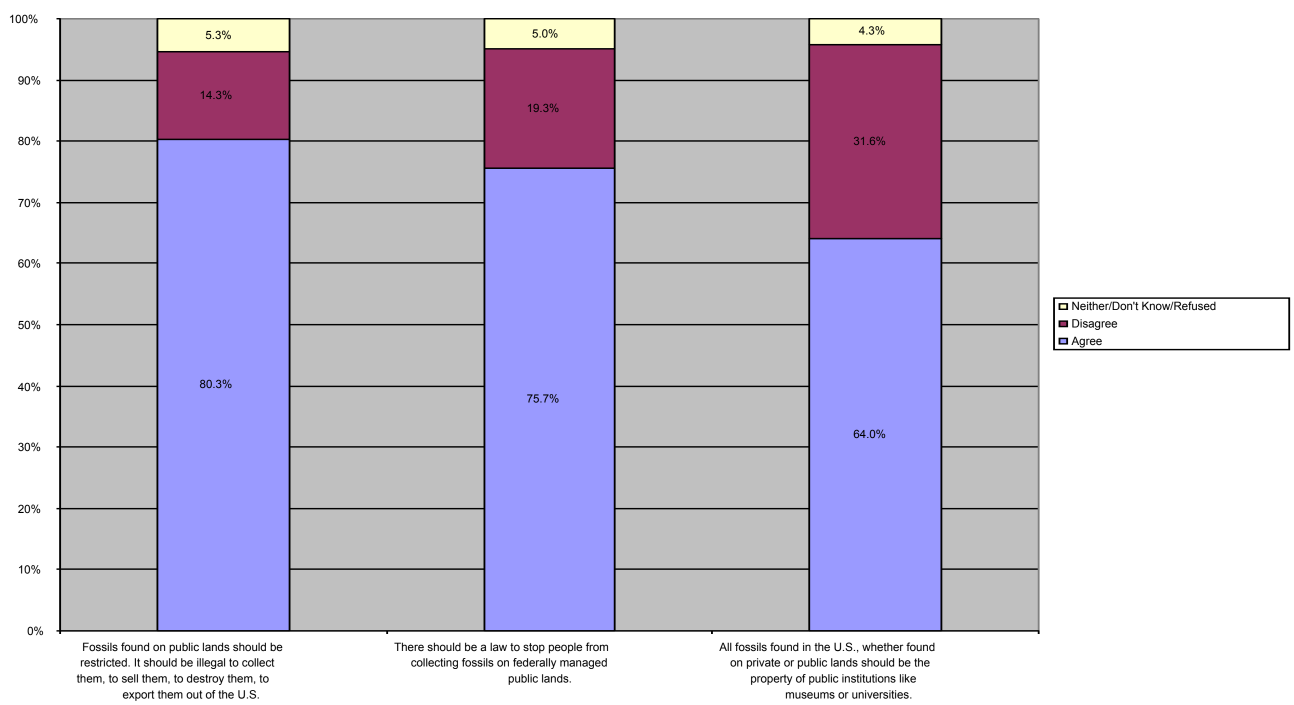


Figure 3

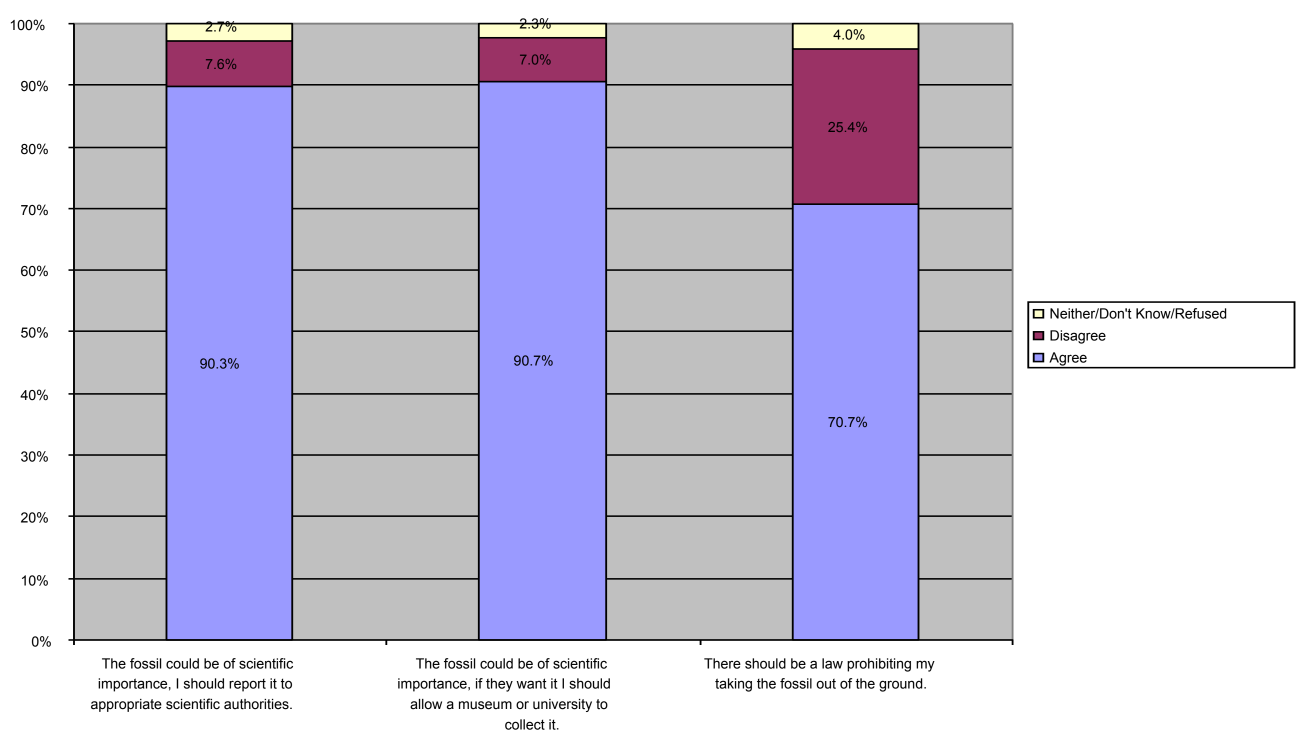


Figure 4

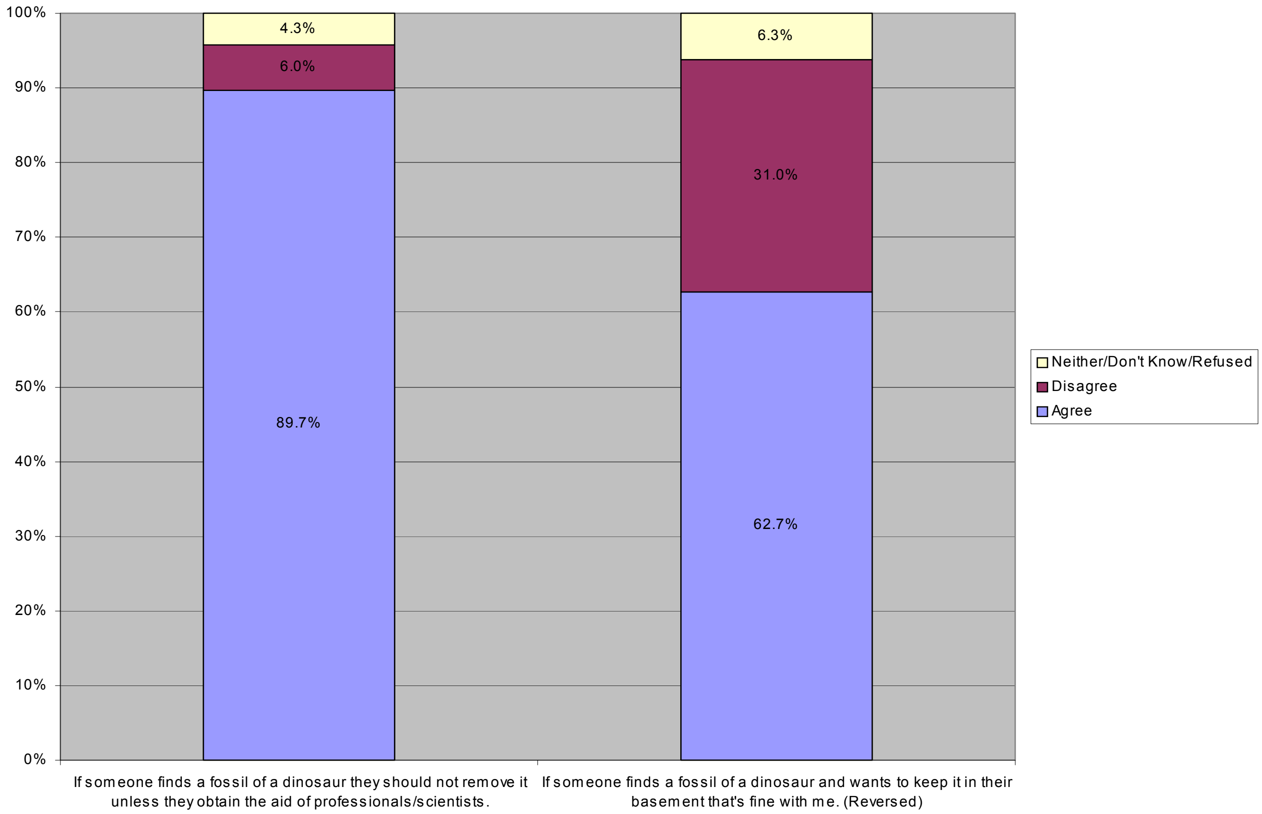


Figure 5

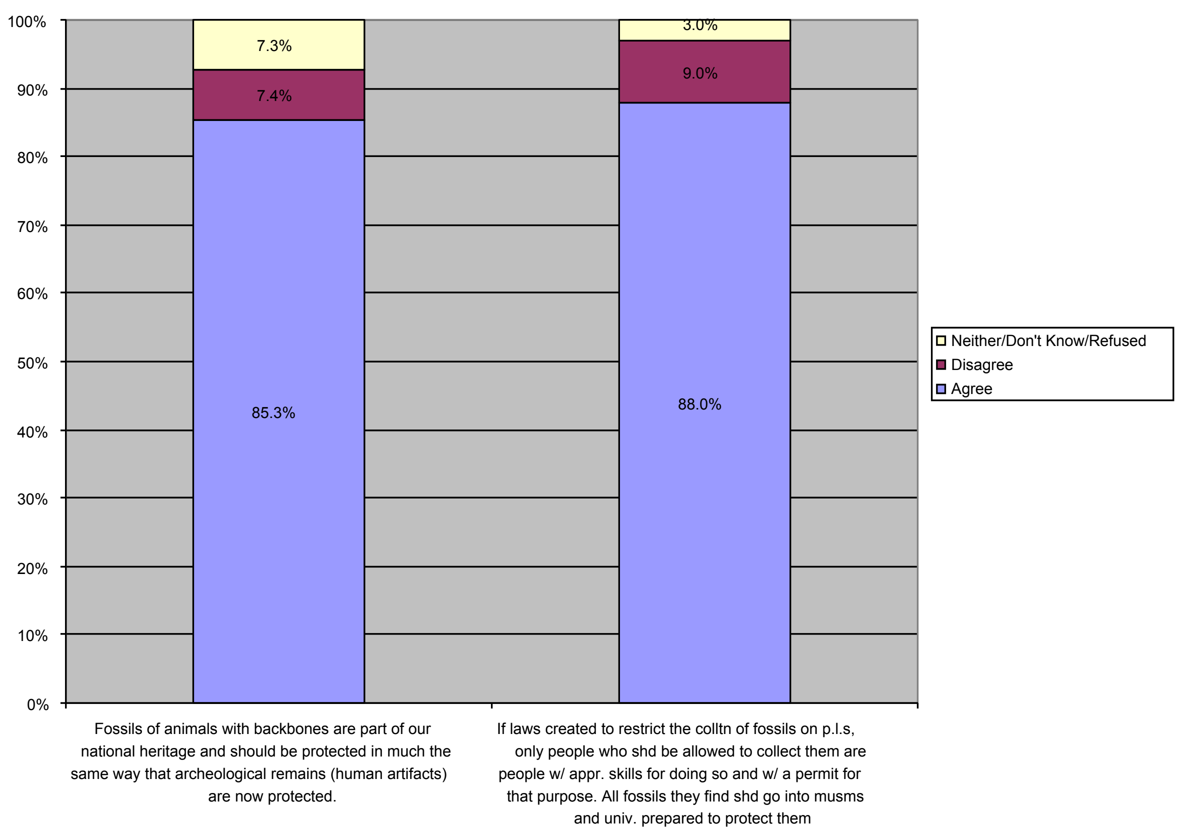


Figure 6

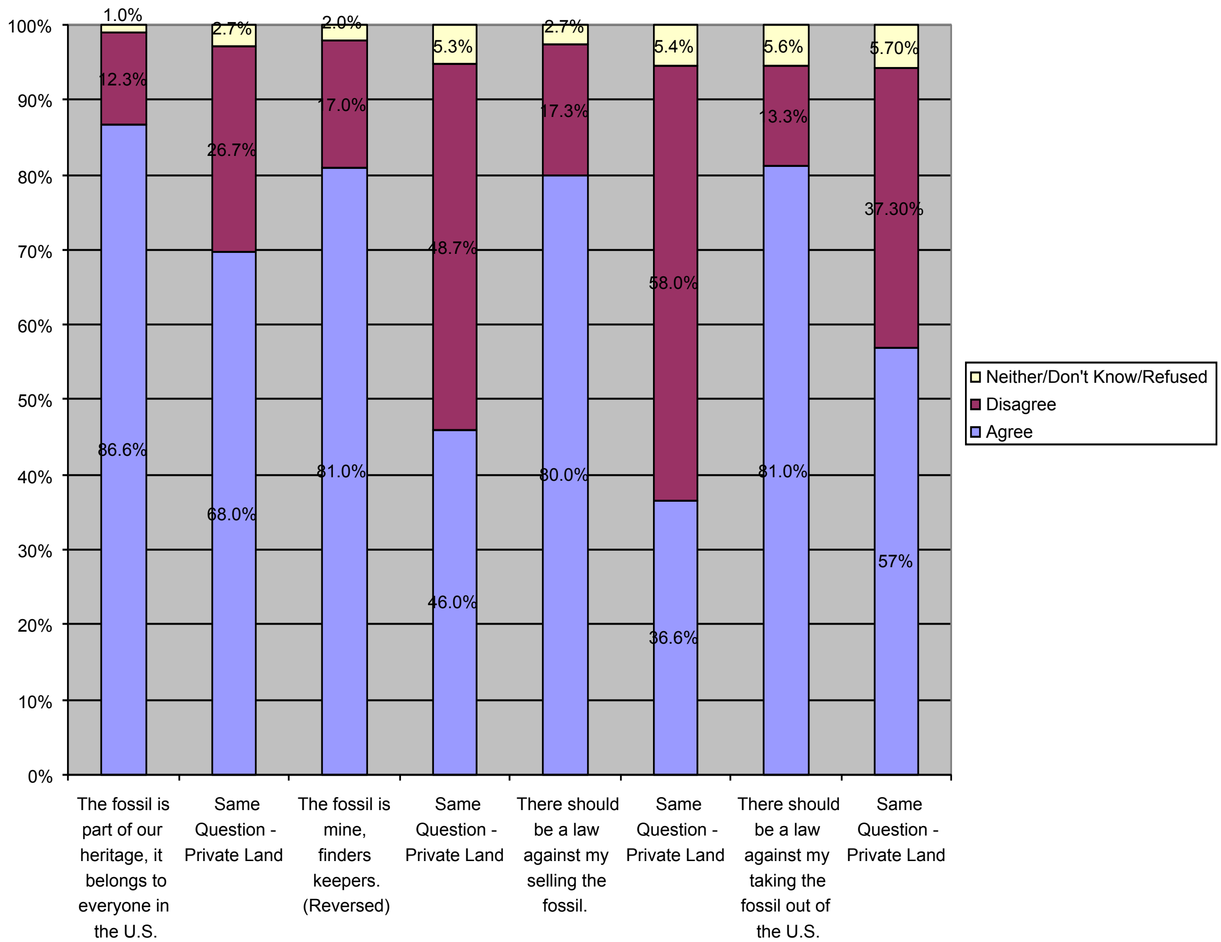


Figure 7

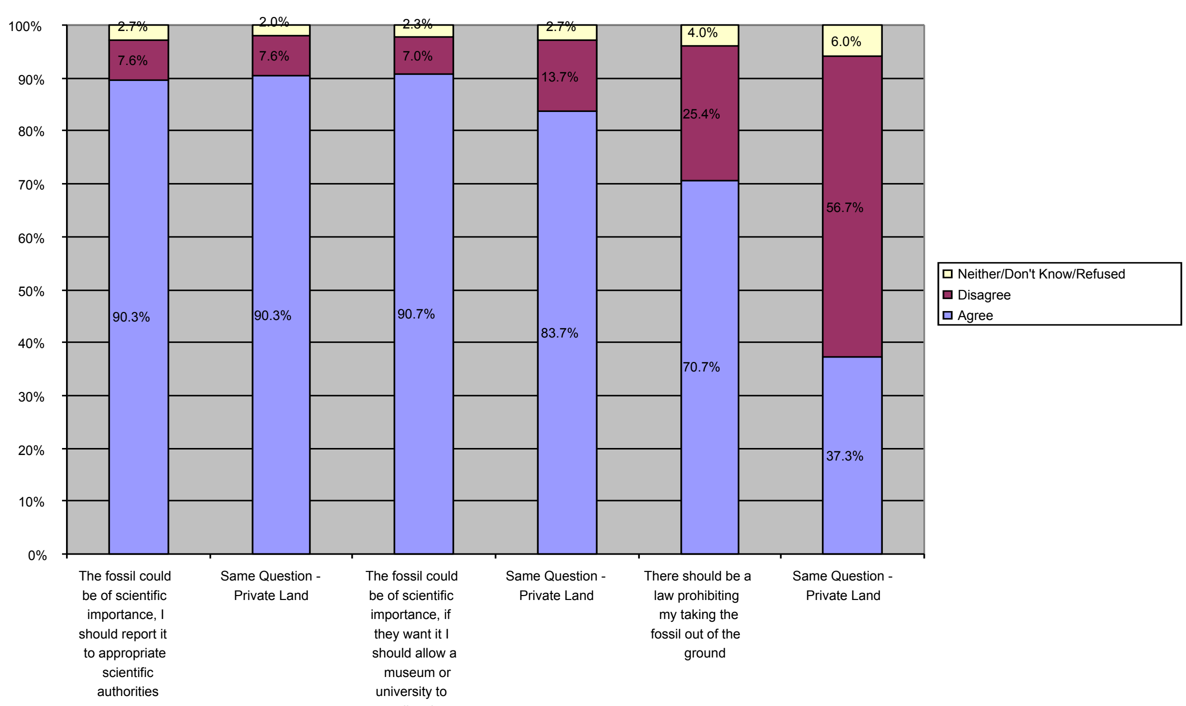


Figure 8

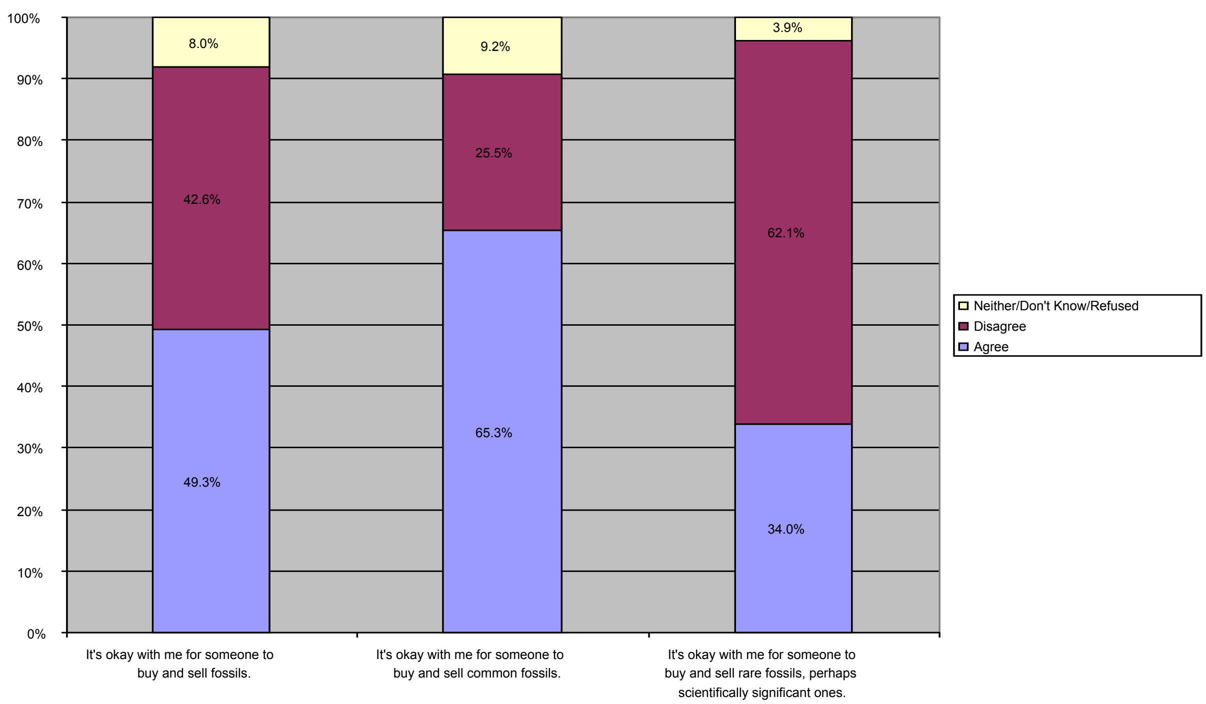
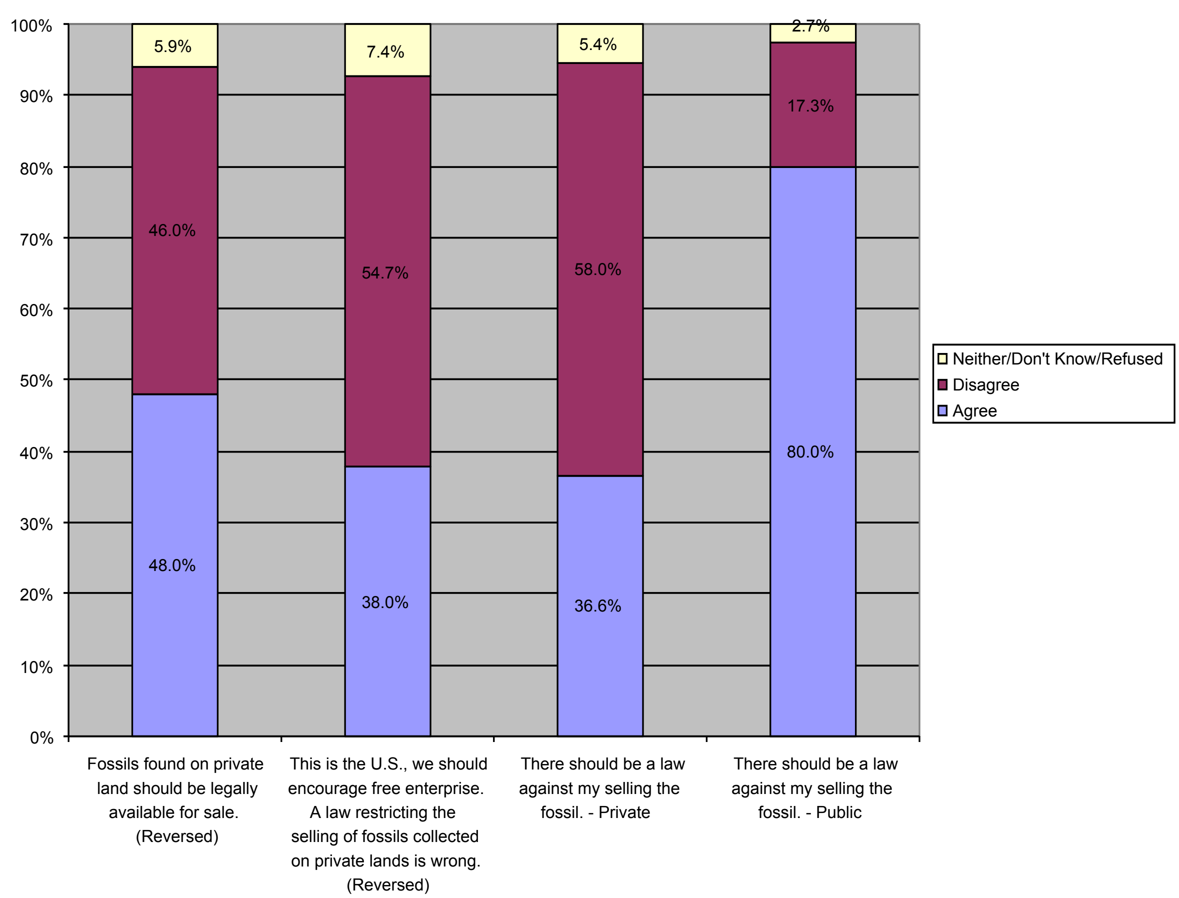


Figure 9



fossils found on publicly owned, federally managed lands should be collected only by qualified personnel, and should remain in the public trust.

REFERENCES

Babbit, B., 2000. Report of the Secretary of the Interior: Fossils on Federal and Indian Lands.

Badgley, C. AND T.J. VLAMIS, 1997. Keep Public Access to Dinosaurs' Treasures. Letter to Editor, Christian Science Monitor, November 17.

H.R. 2943, 104TH CONG., 2ND SESS. 1996.

Paleontological Society and Society of Vertebrate Paleontology, 1999. Joint Position Statement by The Paleontological Society and The Society of Vertebrate Paleontology on Paleontological Resources on U.S. Public Lands.

S. 1569, 98TH CONG., 1ST SESS. 1983.

S. 3107, 102ND CONG. 2ND SESS. 1992.

Society of Vertebrate Paleontology, 1994. Bylaws, Article 9.

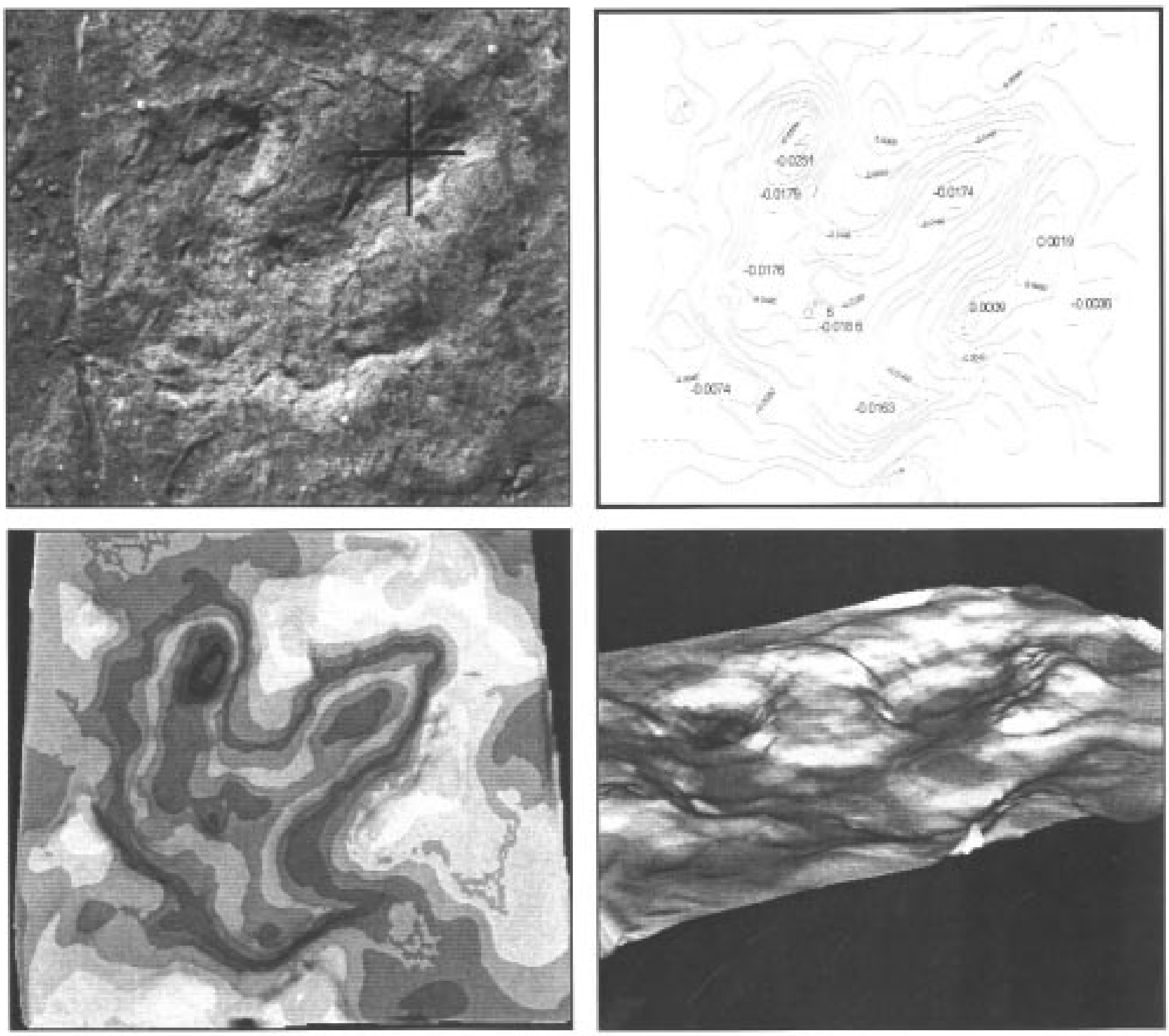
Society of Vertebrate Paleontology, 2000. Minutes of 1999 Annual Meeting.

Vlamis, T.J., J.J Flynn, AND R.K. Stucky. Protecting the Past: Vertebrate Fossils as the Public Trust. Museum News 79, 3:54-57, 69, 71.

As the nation's principle conservation agency, the Department of Interior has responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for enjoyment of life through outdoor recreation. The department assesses our energy and mineral resources and works to ensure that their development is in the bests interests of all our people. The department also promotes the goals of the Take Pride in America campaign by encouraging stewardship can citizen responsibility for the public lands and promoting citizen partcipation in their care. The department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

NPS D-2228 September 2001

PROCEEDINGS OF THE 6TH FOSSIL RESOURCE CONFERENCE



Copies of this report are available from the editors.
Geological Resources Division
12795 West Alameda Parkway
Academy Place, Room 480
Lakewood, CO 80227
Please refer to: National Park Service D-2228 (September 2001).

Cover Illustration
Photo of Red Gulch Dinosaur Tracksite footprint (upper left); digital contour of track (upper right); Digital Terrain Model of track, planar view (lower left); and Digital Terrain Model of track, oblique view (lower right).

2001

a fossil odyssey

PROCEEDINGS OF THE 6TH FOSSIL RESOURCE CONFERENCE

EDITED BY

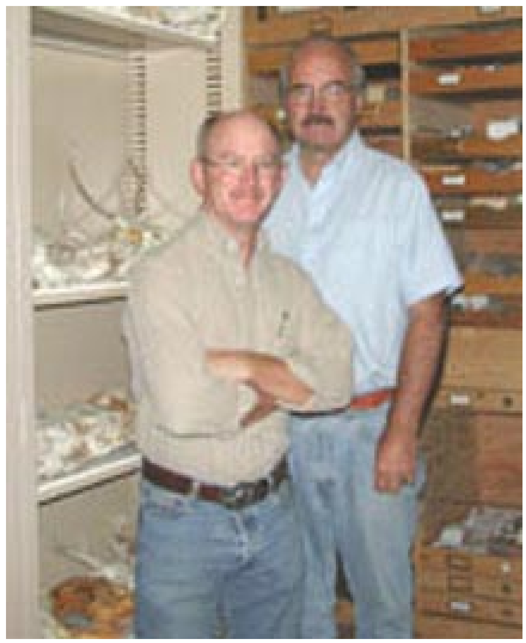
Vincent L. Santucci
National Park Service
PO Box 592
Kemmerer, WY 83101

AND

Lindsay McClelland
National Park Service
Room 3223 - Main Interior
1849 C Street, N.W.
Washington, DC 20240-0001

Geologic Resources Division Technical Report
NPS/NRGRD/GRDTR-01/01
September 2001

CONTENTS



To Dr. Jim Mead
and
Dr. Larry Agenbroad
Northern Arizona University

INTRODUCTION

In 1986, the National Park Service organized the first Fossil Resource Conference hosted at Dinosaur National Monument. Fifteen years and five conferences later, the concept has evolved and broadened in scope. The somewhat regular Fossil Conferences have clearly promoted partnerships between the various federal, state, and local land managing agencies, as well as fostering the relationships between those agencies and the professional and avocational paleontological communities.

The 6th Fossil Resources Conference theme is "2001 A Fossil Odyssey". The new millenium has inspired us to look forward and develop a vision for the future. The conference planning committee hopes that this meeting in Grand Junction, Colorado, will continue to build upon the successes of the previous Fossil Conferences.

The management of paleontological resources on public lands, including research, protection, public education, and recreation continues to experience a renaissance in both the government and the science. Leaders within the Bureau of Land Management, Bureau of Reclamation, National Park Service, U.S. Forest Service, U.S. Geological Survey, and the Smithsonian Institution have worked both independently and collectively to forge a new future for the fossil record.

This volume represents a sample of the scientific and resource management work related to fossils and public lands. Each new discovery, whether it forces us to change our textbooks or the direction of a hiking trail, contributes to our understanding of the history of life. Our ability to provide up-to-date paleo-information to enthusiastic groups of third graders is directly related to the work of our academic partners.

In recognition of the scientific contributions to paleontology on public lands, this volume is dedicated to two paleontologists that have each made significant contributions to paleontology on public lands, Jim Mead and Larry Agenbroad. Jim began working on the Colorado Plateau in 1974. Over the past quarter century, Jim has assisted the BLM, NPS, and USFS on a variety of paleontological projects including his long term work in Rampart Cave, Grand Canyon National Park. Jim is the Director of the Quaternary Science Program at Northern Arizona University and an editor for the Journal of Paleontology. Similarly, Larry's career is highlighted with many important discoveries and accomplishments on federal lands. As the founder of the Quaternary Studies Program at Northern Arizona University, Larry established strong links to the federal agencies on the Colorado Plateau and in the western United States. Some of Larry's more notable achievements are related to work accomplished on BLM lands in the Grand Gulch area, in Bechan Cave in Glen Canyon National Recreation Area, and the pygmy mammoth research at Channel Islands National Park. Both Jim and Larry have also nurtured a generation of young geologists and paleontologists who are now key partners with federal agencies. We extend our tremendous appreciation to Dr. Mead and Dr. Agenbroad.

Thank you to all the authors contributing original manuscripts for publication in this 6th Fossil Resource Conference Proceedings Volume. Additional thanks to the all those who reviewed the manuscripts and provided suggestions to the authors. Finally, it was a pleasure to work with the conference planning team including Peter Ambrose, Mike Selle, Harley Armstrong, Greg McDonald, and John Foster.

Vincent L. Santucci and Lindsay McClelland